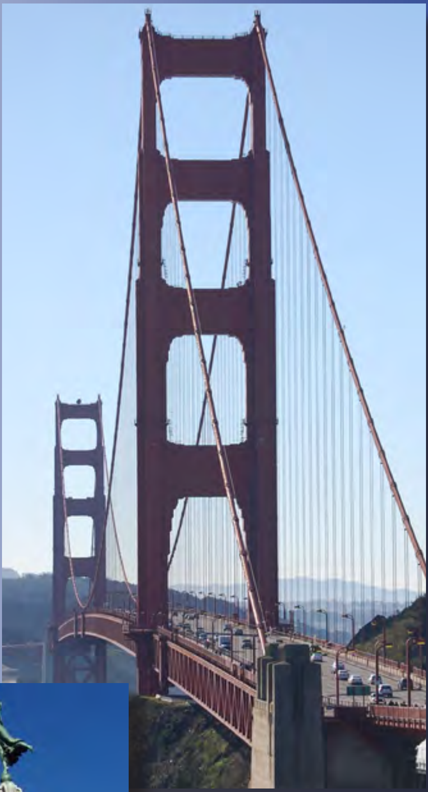
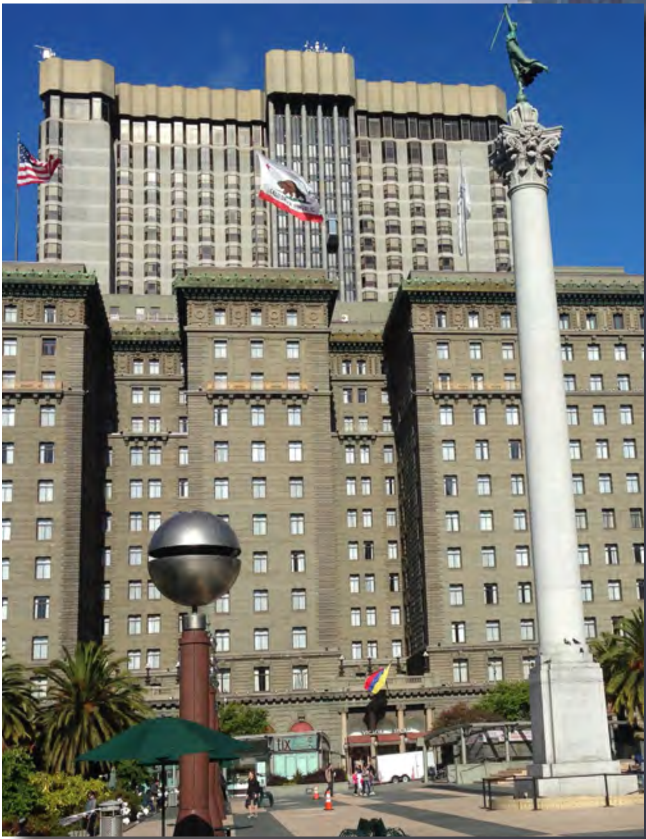
49th US Rock Mechanics/ Geomechanics SYMPOSIUM

28 June–1 July, 2015
San Francisco

american rock mechanics association





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WELCOME TO SAN FRANCISCO 2015

It is my pleasure to welcome you to San Francisco for the 49th US Rock Mechanics/Geomechanics Symposium. Our multidisciplinary, international annual meeting is the focal event for the rock mechanics and geomechanics communities. Here you will meet a diverse group of professionals and students from around the world, specializing in civil, mining, petroleum, geological and geophysical fields.

Special thanks go out to the members of the technical committee, Alvin Chan, Russ Detwiler, Greg Hasenfus and Haiying Huang. Their efforts allowed us to build our strongest technical program yet with a record 359 papers that cover everything within the realm of rock mechanics, rock engineering and geomechanics. You will see presentations addressing challenges in subsurface energy spanning petroleum, geothermal and carbon storage and utilization. As always, our civil- and mining-related sessions continue to be a strong focus for this meeting, thanks to this committee's hard work.

Thanks also to Marisela Sanchez-Nagel for leading the awards committee and Ghazal Izadi for arranging the technical tours. Thanks to Bill Dershowitz, treasurer, and Wayne Gibson for handling exhibits. I am especially grateful to Peter Smeallie, executive director of ARMA, for his seasoned assistance keeping our preparations on track.

San Francisco has become a home, of sorts, for our symposium in recent years. Many of you will have already visited this fine city for this meeting or other engagements. Whether this is your first time here or not, I strongly encourage you to take time to enjoy the city and its surroundings.

Thank-you for joining us in San Francisco and I wish you a pleasant and productive stay,

Joe Morris
Chair of the 49th US Rock Mechanics/Geomechanics Symposium
Computational Geosciences Group Leader
Lawrence Livermore National Laboratory

ACKNOWLEDGEMENTS

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American Rock Mechanics Association

KEYNOTE SPEAKERS

James R. Rice, MTS Lecturer
Harvard University

Kate Hadley Baker
BP (ret) and ExxonMobil (ret)

Christopher Mark
U.S. Mine Safety and Health Administration

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University of California, Berkeley

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Haiying Huang
John McLennan
Michael Murphy

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Marisela Sanchez-Nagel

Career Corner/ Rock Jeopardy
Organized by the Future Leaders

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Ivan Gil
Yanhui Han
Michael Murphy
Maria-Katerina Nikolinakou
Chi Hyun Park
Josh Taron
Dale Walters

Workshop/Short Course Organizers

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Omid Mahabadi
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The 49th U.S. Rock Mechanics/Geomechanics Symposium is pleased to acknowledge the following corporate sponsors. In addition, Itasca IMaGE is sponsoring the Career Corner; David Yale from ExxonMobil is sponsoring the Student Rock Jeopardy Contest. To all our sponsors, our sincere thanks.

Agapito Associates Inc., *Sponsor of the 30 June Symposium Awards Banquet*

Golder Associates, Inc., *Sponsor of three Coffee Breaks*

Itasca International Inc., *Sponsor of the Symposium Delegate Bag*

MTS Systems Corp., *Sponsor of the 28 June MTS Lecture and Reception*

Rocscience, *Donated Registration Lanyards*

EXHIBITORS

ESG Solutions
www.esgsolutions.com

Engineering Seismology Group, (ESG) monitors and locates seismicity in mines helping engineers to understand how rockmass is responding to mining activities. This information enables engineers to effectively plan mine operations, decrease costs, assess hazards, and reduce risk.

GCTS Testing Systems
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GCTS provides a full line of computer servo-controlled testing systems for rocks, soils, pavements, and construction materials. Advanced systems for Triaxial, Direct Shear, Point Load, Indirect Tension, Hydraulic Fracture, Poly-Axial, Hollow Cylinder, Ultrasonic, and other specialized equipment including high-pressure/high temperature triaxial cells. For more information about our testing equipment, please visit our web site at www.gcts.com

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Golder is a global, employee-owned organization providing independent consulting, design, and construction services in our specialist areas of earth, environment, and energy.

Itasca
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Itasca is a global, employee-owned, engineering consulting and software firm working primarily with the geomechanics, hydrogeological and microseismics communities. We solve problems in many industries including mining, civil engineering, oil & gas, manufacturing, and power generation.

EXHIBITORS continued

Lawrence Livermore National Laboratory
www.llnl.gov

Lawrence Livermore National Laboratory has a mission of strengthening the United States' security by developing and applying world-class science, technology, and engineering. This includes advancing our nation's security by innovating science and technology solutions to improve national energy security and surety while reducing environmental impact. We have major research programs in unconventional oil and gas, renewable and sustainable energy, advanced vehicle technologies, materials for energy, energy security, energy systems analysis and nuclear energy.

MALA GeoScience USA, Inc.
www.malags.com

MALA GeoScience USA, Inc. is the North American representative for Reutech Mining's Movement and Surveying Radar (MSR) systems. The MSR systems provide highly accurate, real-time, all weather surveying and slope movement measurements in open pit mines using state-of-the-art radar and surveying technology. All measurements are fully geo-referenced to an accuracy that allows integration of the data with the Digital Terrain Mapping tools of the mine.

MTS Systems Corp.
www.mts.com

MTS is a leading supplier of rock mechanic test systems. Offering extensive expertise in supporting today's most critical geological material evaluation application like ultrasonic velocity, fracture toughness, polyaxial testing and many more. MTS delivers a full range of high-performance hardware, software, and accessories required to meet challenging rock testing requirements.

Maptek
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Maptek is a leading provider of innovative software, hardware and services for the global mining industry. Maptek products are in use at more than 1700 sites in over 65 countries, supported by professional and technical services in a worldwide network of 13 offices. Maptek products include Vulcan™, I-Site™, BlastLogic™, PerfectDig and Eureka™.

Motion Metrics International Corp.
www.motionmetrics.com

Motion Metrics International Corp. specializes in providing advanced monitoring solutions designed to improve the safety, efficiency, and productivity of mining operations all over the world. Their revolutionary 3D-imaging tablet, PortaMetrics™, provides the rock fragmentation analysis of a scene without the need for any reference scaling objects.

PLAXIS Americas
www.plaxis.com

The finite element PLAXIS software is used for geotechnical analysis of deformation and stability of soil and rock, with tools for dynamic and flow analysis. The user-friendly and versatile PLAXIS software can be used for tunnels, excavation, foundations, embankments, and slopes, and has constitutive models available for rock mechanics.

Rocscience Inc.
www.rocscience.com

Rocscience has been creating easy to use, reliable geotechnical software since 1996. We specialize in 2D and 3D analysis and design programs for civil engineering and mining applications. Our high quality programs allow engineers to quickly and accurately analyze surface and underground structures in rock and soil, thereby improving safety and reducing the cost of design projects.

Sandia National Laboratories
www.sandia.gov

Sandia National Laboratories is the nation's premier science and engineering lab for national security and technology innovation. The Sandia Geomechanics Department addresses cross-cutting issues in the geosciences and geoengineering related to rock mass characterization, rock mechanics, development of numerical codes and numerical simulations, validation of material models and design procedures, and in situ measurements and monitoring. The Geomechanics Department emphasizes: characterization of natural fracture systems; identification and modeling of rock deformation and failure processes; laboratory determinations of thermomechanical and transport properties of competent rock and natural fractures, including studies of coupled effects; extrapolation of nano-scale laboratory measurements to field conditions; in situ stress measurements and evaluation of in situ conditions; and laboratory experimental studies.

Simpleware Inc.
www.simpleware.com

Simpleware develops world-class software solutions for image processing and model generation in Materials Science. The software can be used to easily visualise, quantify, segment, process and mesh image data for e.g. composites research, oil & gas exploration and NDE, as well as calculating effective material properties from scanned samples using homogenisation techniques.

EXHIBITORS continued

SOLDATA INC.
www.soldatainc.com

Soldata is a world leader in real time automated geotechnical and structural monitoring. Projects included tunnels, mines, bridges, ports, and heritage buildings. Soldata's Geoscope Software provides integration of all known sensors, AMTS, and radar under one software platform.

TNO DIANA BV
www.tnodiana.com

DIANA (DIsplacement ANAlyzer) is a proven finite element software package utilised for a range of problems arising in the Geotechnical, Oil and Gas sector. DIANA has been used for well bore and reservoir solutions and hosts extensive material and element libraries, linear/non-linear capabilities and 2D/3D modelling features for CAD interoperability.

Weatherford Laboratories
www.weatherfordlabs.com

Weatherford Laboratories rock mechanics labs provide core-based testing and analyses helping operators optimize the reservoir and enhance production. Weatherford Laboratories offers a variety of testing relevant to hydraulic fracture design, wellbore stability, sand production, proppant quality, as well as other reservoir engineering and geophysical applications for conventional and unconventional reservoirs.

GENERAL INFORMATION

Maps

Local maps are available from the hotel.

Transportation, Parking, Restaurants

The Powell Street BART/MUNI subway station is three short blocks from the Westin St. Francis. Bus route maps are available from the hotel. Parking is available for a fee within the hotel and in neighboring garages, but is very expensive. San Francisco has no shortage of world-class restaurants and quick and easy lunch shops. The concierge desk has a list of nearby restaurants.

Registration and Speaker Ready Room

On-site registration is available during the following hours:

- Saturday, 27 June — 7:30 am – 10:00 am
- Sunday, 28 June — 7:30 am – 9:00 pm
- Monday, 29 June — 7:00 am – 6:45 pm
- Tuesday, 30 June — 7:00 am – 6:30 pm
- Wednesday, 1 July — 7:00 am – 2:00 pm

The speaker ready room is located in the Borgia Room just off the Italian Ballroom registration area on the Mezzanine level. A laptop and projector will be available. The speaker ready room will be available during the same hours as the registration desk. Please see the registration desk for access to this room.

Exhibit Hall

Colonial and Italian Ballrooms--The exhibit hall hours are:

- Sunday, 28 June — 7:00 pm – 9:00 pm
- Monday, 29 June — 9:30 am – 6:30 pm
- Tuesday, 30 June — 9:30 am – 4:30 pm

Speakers Breakfast

Alexandra Room--Podium speakers and session chairs are required to attend the speakers' breakfast on the day of the speaker presentation. Please bring the appropriate ticket. Breakfasts begin at 7:00 am in the Alexandra Room on the 32nd floor of the Tower Building of the hotel. Tables will be identified by session number. Speakers will load presentations via a portable USB storage device to the session laptop. In addition to uploading presentations, speakers will be able to meet the session chair(s). Speakers should bring 2 or 3 written biographical sentences, so that the session chair can prepare an introduction.

Career Corner

Exhibit Hall--Don't miss the Career Corner scheduled for Monday, 29 June, 6:00–6:30 pm in the exhibit area. Participation in the Career Corner is a great way to connect and network with representative of employing organizations. Candidates interested in rock mechanics/ geomechanics-related positions are encouraged to post a current resume to the bulletin boards where employers will post career opportunities in their companies or organizations. During the poster sessions, volunteers from ARMA's Future Leaders group will be around to facilitate communications, offer advice on resume writing and interview preparation, and discuss career outlook. For students – Please bring your resumes in hard copy. All students who post their resumes will be automatically entered into a drawing for a raffle prize donated by Itasca Houston. For employers – simply post a job opening on the cork board.

Trivia Jeopardy

Exhibit Hall--Student Trivia Jeopardy! Monday, 29 June, 6:30pm. This year, our annual ARMA student-trivia contest is going to be a Jeopardy-style game! Question categories include: Engineering Basics, Rock Mechanics, Mining, and Petroleum. The winning team will earn a cash price of $250. The game is organized by the ARMA Future Leaders, and the prize is kindly sponsored by David Yale of ExxonMobil.

Short Courses

One short course is offered:

- Saturday, 27 June--Short Course: Rock Fracture Process Modeling Using FDEM—Yorkshire Room

Separate registration required.

Workshops

There are three workshops offered:

- Saturday, 27 June--Workshop on Geomechanics in Unconventionals for Industry Professionals: From Characterization to Production—Elizabethan Rooms
- Sunday, 28 June--Workshop on Digital Rock Physics Derived Rock Mechanics Properties—Elizabethan D
- Sunday, 28 June--Workshop on How to Give an Effective and Engaging Presentation—Elizabethan C

Separate registration required.

TECHNICAL TOURS

Technical Tours

- Saturday, 27 June--Technical Tour 1: Faulting in San Francisco Bay Area Tour
- Sunday, 28 June--Technical Tour 2: San Francisco Bay Geologic Engineering Tour
- Thursday, 2 July--Technical Tour 3: The Geysers/Napa Valley

Groups for the technical tours will leave from the Post Street Entrance.

Technical Tour 1
Faulting in San Francisco Bay Area/Winery Tour with Andy Rathbun
Saturday, 27 June; 9:30 am - 6:30 pm

This technical tour will explore the transition from creep to seismic faulting and view surface manifestations of fault creep and the interior of an ancient fault zone. This all-day tour will include fault-offset features in sidewalks and buildings in the town of Hollister, Calif., a visit to the DeRose Winery for a tasting and look at how the creeping fault is damaging their buildings, and a look at the Corona Heights Fault, an approx. 100 ft. tall by 300 ft. long slicken surface in Franciscian chert. Time permitting, other possible sites include sag ponds, scarps, gouge zones, and Mission San Jan Bautista.

Technical Tour 2
San Francisco Bay Geologic Engineering Tour with Richard Goodman,
Ed Medley, Dale Markum and John Wallace
Sunday, 28 June; 8:00 am - 5:00 pm

This technical tour will include selections from the following locations: Rock stability problems from historic quarry cuts into Telegraph Hill; Fort Point and the Golden Gate Bridge serpentinites; Franciscan Melange at Cliff House and Sutro Baths; Rock slope repair in chert and shale near Twin Peaks (optional stop at Twin Peaks if time and weather permit); Coastal defenses at Pacifica; The Devil's Slide and decomposed granite and faulted coastal terraces of Montara Beach. Richard Goodman, Professor Emeritus, University California, Berkeley; Ed Medley, Terraphase Engineering; and Dale Marcum and John Wallace, Cotton, Shires and Associates will lead the tour.

Technical Tour 3
Geysers/Napa Valley
Thursday, 2 June; 6:30 a.m. – 6:30 p.m.

This tour will feature a special technical visit to the Geysers, site of a recent Enhanced Geothermal demonstration project. The tour will also include a stop at the Visitors Center, the Sonoma Overlook, the Fumaroles and boiling springs, the Little Geysers and the dead tree thermal zone. Lunch will be provided at the Geysers. The second part of this technical tour will feature a visit to the Palmaz Vineyards, a well-known and respected a Napa Valley winery. Palmaz Vineyards' winemaking and aging take place within the living rock of Mount George in a flawlessly engineered maze of tunnels and lofty domes.

SPECIAL ACTIVITIES

Special Activities

There are four special activities offered:

- Saturday, 27 June--Major League Baseball: Giants vs Rockies
- Sunday, 28 June--Alcatraz: “The Rock”
- Monday, 29 June--An Evening on Fisherman’s Wharf: Dinner at the Franciscan Restaurant
- Tuesday, 30 June--San Francisco Highlights

Groups for the special activities will leave from the Post Street Entrance.

Other Scheduled Events

- Sunday, 28 June--ARMA Board of Directors Meeting--Essex
- Sunday, 28 June--ISRM Petroleum Geomechanics Commission Meeting--Essex
- Monday, 29 June--Lunch Meeting of the ARMA Publications Committee--Cambridge
- Monday, 29 June--ASCE Rock Mechanics Committee Meeting—Bristol
- Monday, 29 June—Lunch Meeting of the Houston 2016 Organizing Committee—Oak Room Restaurant/Board Room
- Monday, 29 June--Career Corner—Exhibit Hall
- Monday, 29 June--Student Rock Jeopardy Contest—Grand Ballroom
- Monday, 29 June--ARMA Fellows Dinner and Meeting--Farallon Restaurant
- Tuesday, 30 June--Lunch Meeting of the ARMA Future Leaders--Hampton
- Wednesday, 1 July—Lunch Meeting of the Houston 2016/SF 2015 Organizing Committees—Hampton

SPECIAL ACTIVITIES

Special Activity 1
Take Me Out to the Ball Game! Giants vs. Rockies
Date: Saturday, 27 June 2015; 12:00 noon – 5:00 pm
The 2014 World Champion San Francisco Giants take on the Colorado Rockies at AT&T Park in downtown San Francisco. Watching America's favorite pastime played in "America's most beautiful ballpark" will ensure an exciting evening regardless of the winning team. A deluxe mini-coach will convey you to San Francisco's Embarcadero, where the intimate brick stadium rises at the water's edge. Seats have been reserved in the View Section. At the end of the game, the mini-coach will be standing by to return you to the hotel.

Special Activity 2
Alcatraz: "The Rock"
Date: Sunday, 28 June 2015; 11:30 am – 3:30 pm
On this excursion, you will be "sentenced" to a "short term" on the notorious Alcatraz Island federal penitentiary. From the San Francisco waterfront, you will take a short ferry ride across the chilly waters of the San Francisco Bay to "the Rock." Here you will visit the cells once occupied by some of the nation's most infamous criminals. On this austere wind and fog ridden island, it is easy to see why few attempts were made to escape into the treacherous bay with its undertows and turbulent waters. An expertly created audio tour contains interviews with former prisoners and guards from "the Rock," providing fascinating insight into prison life in the middle of the San Francisco Bay. After your "release" from Alcatraz, the mini-coach will be standing by to return you to your hotel.

Special Activity 3 was cancelled.

Special Activity 4
An Evening on Fisherman's Wharf: Dinner at the Franciscan Restaurant
Date: Monday, 29 June 2015; 6:30 pm – 10:00 pm
Perched at the edge of the San Francisco Bay above bustling Fisherman's Wharf awaits a unique dining experience. Centrally located on Fisherman's Wharf for over four decades, the Franciscan Restaurant recently underwent a three-million-dollar renovation. Everything is new; only the spectacular panoramic views of the City and Bay remain. The spacious tri-tiered dining room and high-beamed ceilings with twenty-foot-high windows allow stunning scenic views from any table. The interior features deep earth tones, brass and iron railing, rich woods, and a flowing wave design throughout. The executive chef prepares fresh seafood caught daily and contemporary California-Italian cuisine. Upon arriving at the Franciscan, you will be escorted to a reserved dining area and seated for a delicious dinner.

Special Activity 5
San Francisco Highlights
Date: Tuesday, 30 June 2015; 9:00 am – 1:00 pm
The forty-nine square miles of San Francisco are a colorful tapestry of steep hills, picturesque houses, clanging cable cars, fishing boats, summer fog, Chinese pagodas, cosmopolitan cafés and breathtaking views. Five continents and three centuries blend together on forty-three hills, waiting to be discovered. On this tour, you will see some of the legendary landmarks of "Everybody's Favorite City."

MONDAY TECHNICAL PROGRAM

Monday, 29 June 2015				
Time	Technical Session 1--California West Petroleum Related Salt Mechanics	Technical Session 2--California East Hydraulic Fracture - Experiments	Technical Session 3--Elizabethan AB Laboratory and Field Testing	Technical Session 4--Elizabethan CD Mining Induced Seismicity and Rock Bursts
08:00 am-08:15 am	800 A. Rodriguez-Herrera Anisotropic seismic velocities around salt structures via stress modelling	444 J. Taylor Injection Induced Fracturing As a Necessary Evil in Geologic CO_2 Sequestration	629 J. Wang Recent Tests and Large Excavations in Underground Research Laboratories and Facilities	169 R. Zelig Rock-burst simulations with 2D-DDA
08:15 am-08:30 am	348 D. Roberts Strategies for Forward Modeling the Evolution of Geological Structures Undergoing Large Deformation	248 H. Viswanathan Integrated Experimental and Computational Study of Hydraulic Fracturing and the Use of Alternative Fracking Fluids	532 F. Rassouli Long-term creep experiments on Haynesville sha e rocks	254 E. Poeck Contribution of shear slip in a widespread compressive pillar failure
08:30 am-08:45 am	159 M. Heidari A Simplified Analysis of Stresses in Rising Salt Domes and Adjacent Sediments	755 R. Medina Flow of high solid volume fraction fluids through fractures and around obstructions	168 A. Fayed Performance of Drilled Shafts Socketed in the Dead Sea Crystalline Salt under Short Term Vertical Loading Condition	374 B. Simser Use of Micro-Seismic Monitoring Data as an Aid to Rock Mechanics Decision Making and Mine Design Verification
08:45 am-09:00 am	347 J. Velilla Uribe Numerical modelling of casing integrity in salt layers including the effects of dissolution and creep	294 J. Stormont Laboratory measurements of flow through wellbore cement-casing microannuli	666 P. Dickson Innovative *In Situ* Stress Testing Using Unconventional Equipment and Procedures for High-Pressure Hydropower Tunnels	394 Z. Hosseini Induced Microseismic Monitoring in Salt Caverns
09:00 am-09:15 am	513 D. Melo Finite Element analysis of casing-in-casing integrity due to annulus pressurization by means of Salt Creep	65 L. Frash True-Triaxial Hydraulic Fracturing of Niobrara Carbonate Rock as an Analogue for Complex Oil and Gas Reservoir Stimulation	148 S. Mighani Nanoindentation Creep Measurements on Shale	650 O. Hosseini Rock burst of underground pillars
09:15 am-09:30 am	108 M. Nikolinakou Stress changes associated with the evolution of a salt diapir into a salt sheet	662 P. Roy Proppant Transport at the Fracture Scale: Simulation and Experiment	639 H. Masoumi Investigation into the Effect of Length to Diameter Ratio on the Point Load Strength Index of Gosford Sandstone	849 Q. Qi The Technology and Practice of Rockburst Prevention in Chinese Deep Coal Mine

Monday, 29 June 2015				
Time	Technical Session 5--California West Injection & Caprock	Technical Session 6--California East Hydraulic Fracture Modeling	Technical Session 7--Elizabethan AB Rock Mass Behaviors and Characterization	Technical Session 8--Elizabethan CD Cave Mining Geomechanics
11:00 am-11:15 am	331 E. Skurtveit Mechanical testing and sealing capacity of the Upper Jurassic Draupne Formation, North Sea	870 V. Chau Crack Band Approach to Model 3D Hydraulic Fracturing of Gas Shale Stratum	44 E. Marques Weathering Profiles of Some Sandstones from Sunshine Coast, Australia - Morphological and Geotechnical Approach	9 Y. Liu Use of digital imaging processing techniques to characterise block caving secondary fragmentation and implications for a proposed Cave-to-Mill approach
11:15 am-11:30 am	352 T. Defoort A finite element geomechanical study of the brittle failure of a caprock due to deflation	556 J. Rutqvist Comparison of Injection-Induced Fault Reactivation and Seismicity in CO_2 Sequestration and Shale-gas Fracturing	613 Y. Tien Numerical Simulation for Shear Behaviors of Rock Joints under Direct Shear Test	10 Y. Li A joint asperity degradation model based on the wear process
11:30 am-11:45 am	364 J. Donald Qualifying Stress Direction from Borehole Shear Sonic Anisotropy	182 J. Wang The influence of fracturing fluids on fracturing processes: a comparison between gas and water	236 Y. Li A Creep Constitutive Model Considering Geometric Damage Of Fractured Rock Mass And Its Application	257 A. Davies Case Study: Understanding the mechanics behind the rockmass deformation observed in an extraction drive at New Gold's New Afton Mine block cave operation
11:45 am-12:00 pm	112 M. Galarraga Application Of Analytical Probabilistic Method To Estimate Minimum Horizontal In Situ Stress from a Leak-Off Test (Lot) Acquired In A High Inclined Well In A Deepwater Turbidites Oil Field, Offshore Brasil	570 D. Birdsell Numerical Model of Hydraulic Fracturing Fluid Transport in the Subsurface with Pressure Transient and Density Effects	503 T. Zvarivadza Use of Rock Mass Classification in prefeasibility studies: An illustrative study	571 P. Hamdi The Use of Numerical Methods in Simulating the Influence of Geological Structure on the Surface Subsidence Associated with Sub-Level Caving
12:00 pm-12:15 pm	305 A. Bauer Numerical model of extended leak-off test (XLOT)	75 Y. Akbarzadeh A Numerical Study of the Para-meters that Affect the Induced Principal Stresses by Hydraulic Fracturing in a Shale Formation	493 N. Hudyma Investigation of Roughness Algorithms Applied to Joint Roughness Coefficient Profiles for Assessment of Weathering	638 J. Tibbett Investigating Block Caving Geomechanics Using Seismic Space-Time Sequences And Virtual Reality Scientific Visualization
12:15 pm-12:30 pm	843 A. Chan In Situ Stress Measurements during Well Abandonment	713 J. Edmiston Development of a geoperidynamic model for hydraulic fracture	614 Y. Tien Variability of mechanical properties of bimrock	842 Q. He Modeling Interaction between Natural Fractures and Hydraulic Fractures in Block Cave Mining

Monday, 29 June 2015				
Time	Technical Session 9--California West Geomechanics for Unconventionals	Technical Session 10--California East Thermal, Mechanical, Chemical and Biological Processes	Technical Session 11--Elizabethan AB Tunnels and Caverns 1	Technical Session 12--Elizabethan CD Reservoir Geomechanics
02:00 pm-02:15 pm	437 M. Geilikman Stress-dependent permeability model of laminated gas shale	143 H. Memarian Experimental assessment of the influences of temperature on geomechanical characteristics of a carbonate reservoir	480 C. Nussbaum Underground Research Laboratories for conducting fault activation experiments in shales	8 T. Hoeink Horizontal Stress Modeling of Successively Built-up Formations: The Effect of Viscous Relaxation and Depth-Dependent Hardening
02:15 pm-02:30 pm	484 R. Holt Relating Static and Dynamic Mechanical Anisotropies of Shale	490 A. Phillips Biological influences in the subsurface: A method to seal fractures and reduce permeability with microbially-induced calcite precipitation	176 J. Deng Induced Rockbursts and Inherent Rockbursts	342 D. Roberts Investigating the Evolution of Polygonal Fault Systems using Geomechanical Forward Modeling
02:30 pm-02:45 pm	768 R. Chalaturnyk Permeability Variations Associated with Various Stress State during Pore Pressure Injection	727 T. Jones Fracture-aperture alteration induced by calcite precipitation	207 D. Zapf Rock Mechanical Design of Gas Storage Caverns in the Salt Dome Edge Region	426 M. Nassir 3D Modeling of Sand Production in Waterflooding by Coupled Flow/ Geomechanical Numerical Solutions
02:45 pm-03:00 pm	376 S. Bauer Helium-Mass-Spectrometry-Permeameter for the measurement of permeability of low permeability rock with application to triaxial deformation conditions	498 H. Du Microstructure and Micromechanics of Wellbore Cements under Compression and Thermal Loading	396 D. Richards Design and Construction of a Deep Excavation in Extremely Poor Rock Mass	801 A. Onaisi Matching 4D seismic time-shifts in structurally complex overburdens with 3D geomechanica models
03:00 pm-03:15 pm	189 S. Xu Analysis of stress variations with depth in the Permian Basin Spraberry/Dean/Wolfcamp Shale	539 J. Elkhoury Effect of Fracture Heterogeneities on Reactive Flow	615 K. Shou On the Tunnelling in the Weak Slate Formations in Taiwan	219 X. Liu A Comparison of Stress Evolution in Single-layer and Multilayer Buckle Folds
03:15 pm-03:30 pm	351 M. Mendoza A. Pore Pressure estimation in a Tight Sand Reservoir: Neuquen Basin, Case Study	657 A. Oyibo Impact of Compression on Petrophysical and Mechanical Properties of Wellbore Cement Containing Salt	162 Z. Zhang TBM Tunneling in Discontinuous Rock Masses	469 R. Quispe Assessment of stress changes in hydrocarbon reservoirs using analytical methods

Monday, 29 June 2015				
Time	Technical Session 13-- California West Coupled Process Modeling in Petroleum	Technical Session 14-- California East Geothermal: Hurdles to Successful EGS	Technical Session 15-- Elizabethan AB Multiscale Modeling	Technical Session 16-- Elizabethan CD Coastal Subsidence
04:30 pm-04:45 pm	814 J. Prevost Multi-scale X-FEM Faults Simulations for Reservoir-Geomechanical Models	175 B. Valley Relative Importance of THM Effects During Non-isothermal Fluid Injection in Fractured Media	304 B. Tatone A combined experimental (micro-CT) numerical (FDEM) methodology to study rock joint asperities subjected to direct shear	98 K. Thienen-Visser Subsidence due to gas production in the Wadden Sea: How to ensure no harm will be done to nature
04:45 pm-05:00 pm	411 J. Dudley Observation and Modeling of Fluid Flow under Matrix and Fracturing Injections in Unconsolidated Sand	869 B. Damjanac Three-dimensional Numerical Investigation of the Effect of Injection Method on Shear Stimulation of Enhanced Geothermal Reservoirs	229 C. Jiang Numerical study of crack coalescence in rock under quasi-static and dynamic loading by using the distinct lattice spring model	375 G. Marketos Surface subsidence induced by hydrocarbons extraction, and the potential for time-dependent ground deformations
05:00 pm-05:15 pm	763 J. Norbeck Simulation of a Microseismic Depletion Delineation Test	626 Y. Fang Mapping Permeability Tensors in Fractured Geothermal Reservoirs Using MEQ Data	460 R. Hashimoto Development of soil-water coupled NMM-DDA	618 S. Hol Long-term compaction behavior of Permian sandstones - An investigation into the mechanisms of subsidence in the Dutch Wadden Sea
05:15 pm-05:30 pm	607 X. Chang The fully coupled fluid flow and Geo-Mechanics model for simulating simultaneous multiple hydraulic fractures propagation in horizontal wells.	810 K. Im Use of Geodesy to Discriminate Deformation Mechanics in Geothermal Reservoirs	430 K. Farahmand A Calibrated Synthetic Rock Mass (SRM) Model for Simulating Crack Growth in Granitic Rock Considering Grain Scale Heterogeneity of Polycrystalline Rock	436 H. Waal Rate type isotach compaction of consolidated sandstone
05:30 pm-05:45 pm	147 S. Mighani Stress Dependency of Rock Tensile Strength	658 J. Rutqvist Mechanisms of EGS Creation at The Geysers (California) revealed by seismic tomography, spatiotemporal evolution of the microseismic events and geomechanical simulations	716 T. Nakai Simple modeling of time-dependent behavior for normally consolidated soil to structured soil	96 P. Fokker On the Use of Double Differences in Inversion of Surface Movement Measurements
05:45 pm-06:00 pm	244 R. Rahner The effect of poroelastic stress changes on the triggering front of induced seismicity during fluid injection	214 M. Soliman Wellbore instability during plasma torch drilling in geothermal reservoirs	691 J. Ma Numerical study on the heterogeneities of rock material under Brazilian test	307 S. Akl Redistribution of Stresses due to Drilling and Depletion Using Different Plasticity Models

TUESDAY TECHNICAL PROGRAM

Tuesday, 30 June 2015				
Time	Technical Session 17-- California West Hydraulic Fracture Simulation	Technical Session 18-- California East Repository Issues for Nuclear Waste Disposal	Technical Session 19-- Elizabethan AB Dams and Foundations	Technical Session 20-- Elizabethan CD Numerical Modeling - Mining
08:00 am-08:15 am	279 K. Wu Study of multiple fracture interaction based on an efficient three-dimensional displacement discontinuity method	478 C. Nussbaum Microseismicity induced in the Opalinus Clay by a gallery excavation in the Mont Terri underground rock laboratory	131 Y. Liu Long-term stability analysis for high arch dam based on time-dependent deformation reinforcement theory	363 K. Mohamed Numerical Simulation of Deformation and Failure Process of Coal-Mass
08:15 am-08:30 am	126 H. Gu Effect of Fracture Breakdown Pressure on Multicluster Hydraulic Fracturing Treatments	540 A. Fox Decimeter-Scale Analysis Of Geologic Heterogeneity In A Brittle-Ductile Shear Zone, Äspö Hard Rock Laboratory, Sweden	140 J. F. da Silva Clogging of drains and its influence on the stability of concrete dams	418 Y. Xue Underground Mine Roof Crack Formation Simulation with Creep of Rock Mass
08:30 am-08:45 am	558 V. Sesetty Simulation of Simultaneous and Zipper Fractures in SHALE Formations	57 S. Giger Transferring the geomechanical behaviour of Opalinus Clay observed in lab tests and the Mont Terri URL to assess engineering suitability at a potential repository site	164 Y. Chen Study on Weakening Effect of Structural Plane and Stability Analysis for Dam Abutment of Jinping I High Arch Dam	423 E. Poeck Effect of Coal-Rock Interface Properties on Failure Stability of Coal Pillars Expressed in Energy Terms
08:45 am-09:00 am	439 J. Kear A 2D Experimental Method with Results for Hydraulic Fractures Crossing Discontinuities	393 A. Pereira Computer modeling applied in the design of underground salt caverns opened by solution mining for gas storage	196 Y. Pan Impounding Deformation Analysis for Jointed Rock Slope Based on Generalized Effective Stress	552 A. Crockford Calibration of inelastic constitutive behaviour at a late stage mine and the challenges associated with data limited calibration
09:00 am-09:15 am	121 X. Weng Investigation of Shear-Induced Permeability in Unconventional Reservoirs	210 O. Czaikowski Sealing capacity of a seal system in rock salt – Hydraulic impact of the EDZ long-term evolution	616 J. Kovacich Evaluating Foundation-Structure Behavior Using a Jointed Material Model	679 F. Arthur Numerical Estimation of the Strength of St. Peter Sandstone Pillars- A Case Study at Iowa
09:15 am-09:30 am	74 J. Huang Hydraulic Fracture Design Optimization for Infill Wells: An Integrated Geomechanics Workflow	303 F. Hansen Geomechanis Issues Regarding Heat-Generating Waste Disposal in Salt	700 N. Sitar Experimental Evaluation of Rock Erosion in Spillway Channels	855 A. Flatten Applications Of Fully Hydro-Mechanically Coupled 3d Mine And Reservoir Scale, Discontinuous, Strain-Softening Dilatant Models With Damage

Tuesday, 30 June 2015				
Time	Technical Session 21-- California West Hydraulic Fracture Modeling	Technical Session 22-- California East Salt Rock Mechanics	Technical Session 23-- Elizabethan AB Modeling of Fractured Media	Technical Session 24-- Elizabethan CD Hard Rock Ground Control and Rock Slopes
11:00 am-11:15 am	572 O. Omidi An adaptive meshing approach to capture hydraulic fracturing	517 S. Bauer Gas flow measurements through consolidating crushed salt	829 R. Peng Analysis of dam abutment erosion by overtopping water using DD	221 R. Yang A new method to measure tri-axial static strain change based on relative displacements between points for open pit slopes
11:15 am-11:30 am	293 M. Dutko Developing a Framework to Simulate the Hydraulic Fracturing of Tight Gas Reservoirs Based on Integrated Adaptive Remeshing & Combined Finite/Discrete Element Approach	698 W. Minkley Healing of Rock Salt Damage and Applications	636 W. Morgan Modeling Hydraulic Fracturing in Naturally Fractured Reservoirs Using the Discontinuous Deformation Analysis	501 T. Zvarivadza A review of pillar design for platinum mining to enhance stability: A Zimbabwean case study
11:30 am-11:45 am	397 L. Guo Numerical simulation of hydraulic fracturing using a three-dimensional fracture model coupled with an adaptive mesh fluid model	26 F. Laouafa Numerical modelling of salt leaching-dissolution process	542 K. Farahmand Effect of Fracture Dilation Angle on Stress-Dependent Permeability Tensor of Fractured Rock	510 Y. Xu Numerical Simulation of End Constraint Effect on Post-peak Behaviors of Rocks in Uniaxial Compression
11:45 am-12:00 pm	507 J. Zhou Modeling the Interaction between Hydraulic and Natural Fractures using Dual-Lattice Discrete Element Method	87 C. Zhu Fabric-enriched Modeling of Anisotropic Healing induced by Diffusion in Granular Salt	710 S. Nazari Numerical modeling of crack propagation mechanism in jointed rock slopes using indirect BEM and DEM	714 E. Yilmazkaya Development of Cuttability Chart for a Limestone Cutting with Monowire Cutting Machine
12:00 pm-12:15 pm	449 A. Rezaei Investigation of Sequential and Simultaneous Well Completion in Horizontal Wells using a Non-planar, Fully Coupled Hydraulic Fracture Simulator	440 L. Blanco Martin Long-term modeling of coupled processes in a generic salt repository for heat-generating nuclear waste: preliminary analysis of the impacts of halite dissolution and precipitation	84 X. Zhang Coupling of rupture growth and fluid flow along a shear fracture containing structural complexities	793 P. Kulatilake Deterministic and Probabilistic Block Theory Analyses Comparison for an Open Pit Mine Rock Slope in USA
12:15 pm-12:30 pm	297 E. Dontsov Incorporating viscous, toughness, and intermediate propagation regimes into enhanced pseudo-3D model	619 C. Lüdeling Dimensioning principles in potash and salt mining to achieve stability and integrity	585 D. Kumar 3D Simulation of Multiple Fracture Propagation from Horizontal Wells	839 J. Henning Evolution of ground support practices applied to low quality, squeezing rock at depth

Tuesday, 30 June 2015				
Time	Technical Session 25--California West Hydraulic Fracture Novel Technologies & Monitoring	Technical Session 26--California East Coupled Process Modeling	Technical Session 27--Elizabethan AB Geophysical Properties of Rocks	Technical Session 28--Elizabethan CD Deep Mine Rock Mechanics
02:00 pm-02:15 pm	514 N. Nagel On The Importance and Impact of Key Geomechanical Parameters in Unconventional Plays	425 D. Steedman Coupled Euler-Lagrange Simulation of the Response of a Tunnel in Jointed Rock to Explosive Loading	245 A. Modiriasari Monitoring of Mechanically-Induced Damage in Rock using Transmission and Reflection Elastic Waves	553 C. Hume Borehole Breakout Analysis to Determine the In-Situ Stress State in Hard Rock
02:15 pm-02:30 pm	806 M. Fry Discrete Element Modelling of Microseismic Energy Associated with Hydraulic Fracturing in Natural Fractures Reservoirs	123 M. Hu Numerical Manifold Modeling of Coupled Hydro-Mechanical Processes in Fractured Porous Rock Masses	651 S. Nakagawa Extremely slow, dispersive seismic wave propagation within a fluid-filled fracture and their electrokinetic effects	296 K. Xia Dynamic tensile failure of rocks subjected to simulated In situ stresses around underground openings
02:30 pm-02:45 pm	408 J. Hampton Fracture Dimension Investigation of Laboratory Hydraulic Fracture Interaction with Natural Discontinuity using Acoustic Emission	587 M. Fall Coupled Modeling of the Strength Development and Distribution within Cemented Paste Backfill Structure	554 J. Morris Numerical investigation of the relationship between fracture shear compliance and conductivity anisotropy	776 J. Seymour Strength and Elastic Properties of Paste Backfill at the Lucky Friday Mine, Mullan, Idaho
02:45 pm-03:00 pm	141 B. Gonçalves da Silva Development of a test setup capable of producing hydraulic fracturing in the laboratory with image and acoustic emission monitoring	680 T. Smith Thermal-Hydrological-Mechanical Modelling of Shear Stimulation at Newberry Volcano, Oregon	382 S. Shao Acoustic Wavefront Imaging of Orthogonal Fracture Networks subjected to Bi-axial Loading	582 D. Olivares Influence of fine material and vertical loads on the flowability of caved rock
03:00 pm-03:15 pm	612 T. Ito Development of Experimental Apparatus for Real-time Observation of Hydraulic Fracture in Unconsolidated Sands by X-ray CT method	809 C. Bradley Near Field Phenomenology for the Source Physics Experiments	433 O. Saber New high-speed friction experiment capability for study of friction	144 H. Maleki Cavability, the Least Known Engineering Factor Influencing Mine Designs in Secondary Extraction Layouts
03:15 pm-03:30 pm	318 A. Hayatdavoudi Pickling the Gas Shale in Water or Water Vapor	38 E. Vtorushin Mixed Finite Element Method applied to Non-Euclidean Model of Inelastic Deformations	546 C. Barnard Application of Refraction Microtremor (ReMi) for predicting changes in rock characterization in an underground mine.	

Tuesday, 30 June 2015				
Time	Technical Session 29-- California West Hydraulic Fracture Complex Fracture Growth	Technical Session 30-- California East New Developments in Computational Rock Mechanics	Technical Session 31-- Elizabethan AB Acoustic Emissions: Fracture Monitoring from Laboratory to Field Scale	Technical Session 32-- Elizabethan CD Coal Mining Ground Control
04:30 pm-04:45 pm	671 P. Fu Numerical Investigation of a Hydraulic Fracture Bypassing a Natural Fracture in 3D	568 S. Ezzedine Application Of Hpc And Non-Linear Hydrocodes To Uncertainty Quantification In Subsurface Explosion Source Physics	204 G. McLaskey Calibrated acoustic emission system records M -3.5 to M -8 events generated on a saw-cut granite sample	846 Y. Chugh Numerical Modelling of Roof Support Plans at 4-Way Coal Mine Intersections
04:45 pm-05:00 pm	80 M. Babazadeh Coupling Fluid Flow and Geomechanics in a Three-Dimensional Discrete Fracture Network Simulator	487 A. Hedayat Numerical simulation of crack initiation and growth in rock specimens containing a flaw under uniaxial compression	134 J. Fortin What can we learn from ultrasonic velocities monitoring during hydraulic fracturing of tight shale	138 G. Esterhuizen Rapid assessment of roof stability in coal mine entries based on the outcome of validated numerical models
05:00 pm-05:15 pm	132 W. Fu An experimental study on interaction between hydraulic fractures and partially-cemented natural fractures	311 E. Rougier Anisotropic geomaterial deformation formulation for the combined finite-discrete element method in 2D	69 M. Molenda Acoustic Emission monitoring of laboratory scale hydraulic fracturing experiments	241 K. Heasley Calculating Potential Coal Pillar Bumps Using a Local Mine Stiffness Criterion
05:15 pm-05:30 pm	119 G. Izadi Fully 3D Hydraulic Fracturing Model: Optimizing Sequence Fracture Stimulation in Horizontal Wells	111 P. Wang Discrete Element modeling and analysis of shielding effects during the crushing of a grain	502 B. Li Observations of Acoustic Emissions in a Hydraulically Loaded Granite Specimen	497 T. Zvarivadza Coal mine pillar failure patterns explained through probabilistic analysis
05:30 pm-05:45 pm	299 O. Mahabadi 3D simulation of fluid-pressure-induced fracture nucleation and growth in rock samples	302 B. Tatone Verification of the implementation of rock-reinforcement elements in numerical analyses based on the hybrid combined finite-discrete element method (FDEM)	239 M. Rück AE-Rate Controlled Mode II Fracture Propagation Experiments on Granite and Sandstone	240 J. Zhang Ground control in China's coal mine: progress and prospects
05:45 pm-06:00 pm	249 V. Roche 3D modeling of hydraulic fracturing and stress perturbations during fluid injection	536 K. Duan Parametric study of smooth joint parameters on the behavior of inherently anisotropic rock under uniaxial compression condition	474 Y. Xiao Micro-Seismic Monitoring of PDC Bit Drilling Performance during Vibration Assisted Rotational Drilling	

WEDNESDAY TECHNICAL PROGRAM

Wednesday, 1 July 2015				
Time	Technical Session 33-- California West Wellbore & Drilling Mechanics 1	Technical Session 34-- California East Measuring and Modeling Rock Properties	Technical Session 35-- Elizabethan AB Failure Behavior and Constitutive Modeling	Technical Session 36-- Elizabethan CD Mining Geomechanics
08:00 am-08:15 am	366 F. Zhang Wellbore Stability Modeling with a Grain Based Rock Model	790 D. Grégoire Predicting intrinsic and apparent permeabilities from pore size distribution in tight porous materials	150 M. Serati Michell-Fourier Analytical Treatment Of Stresses In The Ring Test Under Parabolic Compression	402 F. Rafeh Numerical creep analysis of chalk cavities accounting for joints degradation
08:15 am-08:30 am	82 M. P. Shahri An Integrated Analytical Workflow for Analyzing Wellbore Stress, Stability and Strengthening	547 S. Osinga Study of geomechanical properties of 3D printed sandstone analogue	231 Y. Zhang Constitutive couplings in unsaturated granular media with crushable grains	488 M. Ghamgosar Investigation the Effect of Cyclic Loading on Fracture Propagation in Rocks by Using Computed Tomography (CT) Techniques
08:30 am-08:45 am	152 Y. Chen Hidden Impact of Mud Loss on Wellbore State of Stresses Disclosed by Thermal-Poro-Elastic Modeling	504 K. Andreassen Rate dependence of dry, oil- or water-saturated chalk	284 A. Fakhimi Size effect on length and width of fracture process zone	623 B. Panda Relationship Between Compressive Strength and Index Properties of Rock
08:45 am-09:00 am	48 S. Gosavi Application of Rock Physics in Wellbore Stability Modeling for Chayvo Field Multi-lateral ERD Wells	597 S. Cho Loading rate dependency of dynamic fracture toughness of rocks	232 S. Thirukumaran Modelling the shear behaviour of sedimentary rock joints under constant normal stiffness conditions	807 S. Warren Correlation of the Rock Mass Rating System (RMR) to the Unified Soil Classification System (USCS) for Geotechnical characterization of Very Weak Rock Masses
09:00 am-09:15 am	174 J. ter Heege Characteristics of mechanical wellbore failure and damage: Insights of discrete element modelling and application to CO_2 storage	634 M. Ghamgosar Effect of Anisotropy on Fracture Toughness and Fracturing of Rocks	157 S. Gheibi Numerical Modeling of Rock Brazilian Test: Effects of Test Configuration and Rock Heterogeneity	464 K. Das Discrete Modeling of Multiple Discontinuities in Rock Mass using XFEM
09:15 am-09:30 am	431 V. Dokhani Effects of Adsorptive Characteristics of Shale on Wellbore Stability	315 K. Roth Fracture Testing in Modes I, II, and III on Escabrosa Limestone	575 S. Esna Ashari Micro-scale modeling of the inelastic response of a granular sandstone	

Wednesday, 1 July 2015

Time	Technical Session 37-- California West Wellbore & Drilling Mechanics 2	Technical Session 38-- California East CO_2 Sequestration - Experiments and Modeling	Technical Session 39-- Elizabethan AB Hazard Prediction and Mitigation	Technical Session 40-- Elizabethan CD Case Histories - Mining
11:00 am-11:15 am	349 G. Schreppers A framework for wellbore cement integrity analysis	290 S. Sobolik Geomechanical Modeling to Predict Wellbore Stresses and Strains for the Design of Wellbore Seal Repair Materials for Use at a CO_2 Injection Site	180 R. Macciotta Remote Structural Mapping and Discrete Fracture Networks to Calculate Rock Fall Volumes at Tornado Mountain, British Columbia	286 L. Rodriguez The Implementation of 30 ft Wide Undercuts at TRJV
11:15 am-11:30 am	110 A. Lavrov Numerical study of thermal stresses in casing-cement-rock system with heterogeneity	569 S. Ezzedine Multiphase Flow In Fractured Porous Media: Application To CO_2 Leakages From Natural And Stimulated Fractures	419 V. Gono Understanding the Correlation between Induced Seismicity and Wastewater Injection in the Fort Worth Basin	410 H. Zhao Evaluation and Selection of Surface and Production Casings for the New Wells at Eti Soda's Beypazari Trona Deposits
11:30 am-11:45 am	118 M. Oyarhossein Wellbore Stress Changes and Microannulus Development Because of Cement Shrinkage	127 Y. Zhang Geomechanical evaluation of fault reactivation potential and uplift at the South West Hub geological CO_2 storage site, Western Australia	792 P. Kulatilake Stability of the rock block system that initiated the Jiweishan landslide in China	690 A. Rai A case study for Northern Nevada single excavation! Shaft-Technical Limit: width and depth?
11:45 am-12:00 pm	301 A. Tallin Impact of Depletion on Integrity of Sand Screen in Depleted Unconsolidated Sandstone Formation	165 E. van der Veer A coupled geochemical-transport-geomechanical model to address caprock integrity during long-term CO_2 storage	820 J. Wallace History And Mechanisms Of Rock Slope Instability Along Telegraph Hill, San Francisco, California	717 R. Kallu Numerical Modeling Technique for Time Dependent Behavior of Weak Rock Masses - A Case Study
12:00 pm-12:15 pm	287 Alexandre Duepohon Stick-slip instabilities in rotary drilling systems	384 L. Buijze Dynamic rupture modeling of injection-induced seismicity: Influence of pressure diffusion below porous aquifers	298 K. Mortezaei Effect of hydraulic diffusivity and slipping zone thickness on thermal pressurization process during seismic slip	852 F. Capdeville-Perez Building a Rock Mass Model for a Large Open Pit
12:15 pm-12:30 pm	5 T. Ait-Ettajer Three Dimension Geomechanical Modeling for Drilling In Carbonate Reservoirs	399 Y. Hao Numerical study of the impact of CO_2-fluid-rock interactions on porosity and permeability evolution in fractured carbonate rocks	441 B. Sadagah Rock slope instability modeling analysis and mitigation at mountainous road, and prediction of debris flows utilizing the satellite image, Saudi Arabia	

Wednesday, 1 July 2015

Time	Technical Session 41-- California West Petroleum-Related Rock Mechanics 1	Technical Session 42-- California East Shale - Experiments and Modeling	Technical Session 43-- Elizabethan AB Tunnels and Caverns 2	Technical Session 44-- Elizabethan CD Fracture Mechanics 1
02:00 pm-02:15 pm	549 J. Hampton Acoustic Emission Monitoring Elucidates Proppant Pack Strength Characteristics during Crush Testing	225 W. Li Modeling of Failure Behavior of Anisotropic Shale Using Lattice Discrete Particle Model	137 Q. Zhang A new 3D constitutive model for rock mass tunnel	190 G. Lu Experimental Demonstration of Delayed Initiation of Hydraulic Fractures below Breakdown Pressure in Granite
02:15 pm-02:30 pm	246 P. Cerasi Sand production delay in gas flow experiments	389 J. Carey Experimental Investigation of Hydraulic Fracturing of Shale with water	209 D. Zapf Salt Structure Information System (InSpEE) as a Supporting Tool for Evaluation of Storage Capacity of Caverns for Renewable Energies - Rock Mechanical Design for CAES and H_2 Storage Caverns	313 E. Rougier FDEM Simulation On Fracture Coalescence In Brittle Materials
02:30 pm-02:45 pm	27 H. Sone Microscopic observations of shale deformation from in-situ deformation experiments conducted under a scanning electron microscope.	312 E. Rougier FDEM simulation on a triaxial core-flood experiment of shale	358 P. Li Soft Ground Shield Driven Tunnel Defect Analysis	746 A. Tarokh Critical pressure and scaling in cavity expansion tests
02:45 pm-03:00 pm	767 M. Alsalman Comparison of Multistage to Single Stage Triaxial Tests	520 S. Kalra Numerical Simulation Study On Co2 Injection For Enhancing Hydrocarbon Recovery And Sequestration In Tight Oil Formation	467 B. Ye Numerical study on long-time deformation characteristics of soft clay around subway tunnel under train vibration load	420 A. Kamali An Investigation of Rough Surface Closure with Application to Fracturing
03:00 pm-03:15 pm	496 F. Amann Dilatancy of clay shales and its impact on pore pressure evolution and effective stress for different triaxial stress paths	653 G. Lackey Modeling Stray Gas Leakage from Wellbores in Colorado Shale Gas Operations	836 J. Pan Optimization of Pipe Roof Design for Gongbei Port Tunnel Excavation	30 E. Holderby Advances in the Use of New-Age Complex Fracture Modeling, Earth Modeling, and Reservoir Simulation Tools as an Asset Well Planning Tool
03:15 pm-03:30 pm	237 P. Cerasi Experimental investigation of cement to rock bonding	228 M. Shimo Gas Transport Characterization of Fractured Rock by In-situ Gas-injection Tests	179 S. Zhou A micromechanical study of the interactions between a hole and a crack under compression using PFC2D	489 P. Papanastasiou The Brittleness Index in Hydraulic Fracturing

Wednesday, 1 July 2015

Time	Technical Session 45--California West Petroleum-Related Rock Mechanics 2	Technical Session 46--California East Uncertainty: Assessment and Quantification/Rock Properties	Technical Session 47--Elizabethan AB Wellbore and Drilling Mechanics 3	Technical Session 48--Elizabethan CD Fracture Mechanics 2
04:00 pm-04:15 pm	362 J. Alvarez Characterization of mechanical properties of rocks using numerical simulations and image analysis	422 M. Mauldon Using Image Windows for the Analysis of Fracture Traces and Fractures	479 Q. Guo Testing Methods for Evaluating Drilling Fluid Effects on Gas Shale Stability	550 O. Vorobiev Modeling dynamic stimulation of geological resources
04:15 pm-04:30 pm	201 A. Soares Numerical Modelling of Rock Mechanics Experiments as an Input for Coupled Hydromechanical Simulation	543 A. Ferrero Some open issues on the design of protection barriers against rockfall	97 X. Shen Integrated 1-D Workflow for Pore-Pressure Prediction and Mud-Weight Window Calculation for Subsalt Well Sections	719 Y. Wang Interpretations of Fracture Initiation and Orientations In a Perforated Deviated Well during Staged Fracturing
04:30 pm-04:45 pm	409 E. Fjaer Static versus dynamic moduli: another piece in the puzzle	652 N. Bozorgzadeh Characteristic Triaxial Strength Of Intact Rock	310 M. Ostadhassan Probabilistic Time-Dependent Thermo-chemo-poroelastic Borehole Stability Analysis in Shale Formations	68 D. Wang Experimental study of fracture initiation and propagation from a wellbore
04:45 pm-05:00 pm	522 M. Fourmeau Influence of indexation and impact energy on bit/rock interface law in percussive drilling: an experimental study	485 K. Kishida Measurements of fracture aperture in granite core using microfocus X-ray CT and fluid flow simulation	345 H. Huang Effect of Rheology on Drilling Mud Loss in a Natural Fracture	222 D. Nikolskiy Boundary element analysis of non-planar three-dimensional cracks using complex variables
05:00 pm-05:15 pm	584 A. Vachaparampil A combined method to measure Biot's coefficient for rock	280 A. Naeimipour Estimation of Rock Strength by Means of Scratch Test	341 J. Todorovic Filter cake behavior during leakage at the cement-rock interface in wellbores	291 J. Bai Coupled geomechanics and fluid flow computational algorithm for modeling hydraulic fracturing with pre-existing natural fractures in unconventional shale reservoirs
05:15 pm-05:30 pm	566 L. Walle Acidizing of hollow cylinder chalk specimens and its impact on rock strength and wormhole network structure	391 M. Shewalla Measure of Friction during Drilling of Rocks	708 W. Zhang Optimizing Drilling Parameters: A Preliminary Model--Drilling Carthage Mable	73 C. Cohen A New Stacked Height Growth Model for Hydraulic Fracturing Simulation.

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Technical Session 1 – California West
Petroleum Related Salt Mechanics

Monday, June 29, 2015, 08:00 am - 09:30 am

Chairs: Maria-Aikaterini Nikolinakou & George Marketos

ARMA 15-0800

Anisotropic seismic velocities around salt structures via stress modelling

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We predict anisotropic velocity perturbations around a salt dome on the edge of the Sigsbee escarpment in the Gulf of Mexico, using a combination of 3D geomechanical modelling and application of rock-physics predictions. The modelling predicts an increase in compressive stress in directions perpendicular to the salt face compared to a model without salt. This stress increase causes an increase in P-wave velocity in the direction perpendicular to the salt wall. Similarly, parallel to the salt wall a decrease in compressive stress is predicted, compared to a salt-less background model. The stress decrease causes a decrease in P-wave velocity in directions parallel to the salt wall. These predictions are compared to observed azimuthal seismic velocity variations from a multi-azimuth seismic survey and a good match between predictions and observations is observed. In so doing, we firmly establish a geomechanical cause to anisotropic velocity perturbations around salt. Ultimately, geomechanically predicted seismic velocities may therefore be used in velocity model building and imaging workflows and are expected to improve seismic images in areas with complex salt tectonics.

ARMA 15-0348

Strategies for Forward Modeling the Evolution of Geological Structures Undergoing Large Deformation

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Forward Modelling is frequently used in studying the evolution of a range of geological structures, from local faults and folds to entire passive margins. The ability to predict the physical formation of geological structures provides significant benefit in understanding the evolution of stress and pore pressure distribution within a field and the material state of the reservoir units. Geometric or kinematic techniques are often used to analyse geological structures but they ignore the mechanical deformation response of the rock strata. In some cases this may lead to the mechanisms responsible for the presence of a particular structure not being fully understood or missed completely, with obvious implications for activities such as hydrocarbon exploration. Many advanced FE element software packages can model the evolution of structures providing the rock deformation can be regarded as small strain. However FM modelling software employing adaptive remeshing technology can overcome these shortcomings and analyse the evolution of geological structures where large deformation of the strata occurs such as salt diapirism, regional and counter regional systems.

Even though Forward modelling technology can predict the formation of geological structures resulting from large deformation, until recently, in some cases, there was a limit to how much large deformation could be accommodated. This was a consequence of the way Forward Modelling technology handled the occurrence of strata thinning as a result of large extensional or shear deformation. This phenomenon, for example, may arise when considering the rise of salt diapirs through multiple overburden layers or the formation of thrust faults. In reality the thinning strata would either be punched through and incorporated into the rising salt body, or reduced to a relatively thin layer acting as a fault plane or décollement. Previous strategies to treat thinning layers utilised a numerical technique in which a user defined minimum thickness was maintained. This could in certain modelling scenarios have the undesirable effect of capping a penetrating diapir or maintaining a thin layer in a developing fault zone. In addition, in order to represent these thin

layers a fine mesh discretisation is required which may considerably extend the computation time required.
This limitation has been overcome by developing an automated methodology to erode thinning strata at the earth's surface or collapsing thinning sub-surface strata once a certain thickness has been achieved. The methodology extends the adaptive remeshing techniques currently used by the *ELFEN FM* modelling suite to encompass adaptive geometric methods that modify the geometry of the domain, automatically removing the thinned layers and replacing it by neighbouring material. In order to successfully achieve the update of the model, consideration has to be given to the mapping of the stress and material state in the region of the removed material with the newly extended neighbouring material. Also, where thinned strata is removed adjacent to a fault surface, contact conditions between the new strata surfaces needs to be initiated and equilibrium conditions satisfied
The technological developments have been successfully applied to problems such as local/regional salt tectonics, as well as the formation of roho systems and fault thrusts.

ARMA 15-0159

A Simplified Analysis of Stresses in Rising Salt Domes and Adjacent Sediments

Mahdi Heidari[1], Maria Nikolinakou[1], Peter Flemings[2], Michael Hudec[1]
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We derive simple analytical solutions for the stress field in and around rising salt domes. We show that the pressure within the dome varies linearly along the dome height and can be calculated from the density profile of adjacent sediments. This salt pressure also defines the stress field in the sediments: the maximum stress lies normal to the dome with a magnitude larger than the overburden stress, and the minimum stress lies circumferential to the dome with a magnitude smaller than the far-field horizontal stress. Even though these solutions are derived under simplified conditions, they provide critical insights into how a rising salt dome changes the stress field within the wall rocks; hence, they are invaluable resources for assessing the results of numerical models and understanding field data near rising salt domes.

ARMA 15-0347

Numerical modelling of casing integrity in salt layers including the effects of dissolution and creep

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This paper presents a methodology to analyze the casing integrity in salt layers considering the effects of creep and dissolution on the borehole clossure. The finite element software ABAQUS was used to perform the simulations. The dissolution was considered both homogeneous and inhomogeneous through a function that turns off the elements located on the wellbore. The progress of material removal obeys to the characteristic dissolution curve of the rock salt studied, and the creep was analyzed with a power law function, available in ABAQUS library. Four cases have been studied: a) homogeneous dissolution of the entire wellbore, b) partial dissolution of the wellbore, c) homogeneous dissolution considering casing standoff and d) homogeneous dissolution for an oval geometry of the wellbore. The results show that the dissolution may slow the contact of the salt with the casing whenever it is homogeneous; and for inhomogeneity condition point loads are generated that increases considerably the stresses on the casing being the critical scenery for the pipe; in addition, with 12 years simulation time, numerical problems occurred due to the high distortions of the finite element mesh being necessary to use adaptive re-meshing techniques to treat such problems. Finally, through a sensitivity analysis, there were identified parameters of greatest influence on the resistance of the casing, such as density of the drilling fluid used, the amount of diluted saline rock and the geometry of the well.

ARMA 15-0513

Finite Element analysis of casing-in-casing integrity due to annulus pressurization by means of Salt Creep

DANIEL MELO[1], SERGIO FONTOURA[1], NELSON INOUE[1], JOREL ANJOS[2]
[1]PUC-RIO, [2]PETROBRAS

Casing integrity is a major concern in wells drilled through evaporites zones due to the salt viscoelastic property, which leads to an increase in load with time. Then the casing string will be subjected to high loads that may compromise the pipe stability forcing it to collapse. Additionally, in a production scenario, the temperature in the production tubing increases due the thermal exchange from the formation fluids. This increase in temperature produces an increase in pressure in the subsequent trapped annulus space. I this scenario, a big concern of the design engineers is predict the consequences of a possible intermediate casing collapse in the integrity of the production tubing, which may lead to serious problems and possibly making any workover infeasible. Therefore this paper focus in the contribution of salt creep in the phenomenon of annuls pressure build up and the consequences of an intermediate casing collapse in the integrity of the production tubing during 30 years of salt creep. The analyses involves FEM considering fluid elements, which can account for pressure build up as the wellbore closes and pressure relief as the casing collapses. At first, casing and tubing collapse pressures are computed individually by FEM and compared to Klever-Tamano and Timoshenko equations so as to validate the model. After validation, different initial stress states and fluid properties (density, bulk modulus) are modeled. For those scenarios, casing collapse pressure is accounted, as well as the pressure that leads to tubing failure or to creep equilibrium. With the analysis, limiting factors such as minimum interior tubing pressure can be estimated so as to not compromise tubing integrity.

ARMA 15-0108

Stress changes associated with the evolution of a salt diapir into a salt sheet

Maria-Aikaterini Nikolinakou[1], Mahdi Heidari[1], Michael Hudec[1], Peter Flemings[1]
[1]The University of Texas at Austin

We study how stresses change as a salt diapir evolves into a salt sheet. We find a reversal in the stress state, as the radial stress changes from being the maximum stress when the diapir is rising, to minimum when the salt sheet is advancing. We study an axisymmetric diapir (dome) with the large-strain Finite Element program Elfen. We model the salt as solid visco-plastic, with the Munson & Dawson model and the sediments as poro-elastoplastic, with a generalized MCC model (SR3, in Elfen). During the salt-dome rise, ongoing sedimentation increases the average density within the basin to values higher than the density of the salt. As a result, the basin over-pressurizes the salt, and this is translated to a horizontal thrust-loading from the salt towards the upper parts of the basin. However, as the diapir evolves into a sheet, the effective height of the salt dome drops by a couple of kilometers; as a result, the stress within the salt decreases. At the same time, the vertical stress within the basin increases substantially because of the weight of the advancing sheet. We hence predict a change in the orientation of the minimum principal stress associated with a switch from horizontal shortening to extension. Furthermore, we show that the ratio of minimum effective principal stress to effective overburden decreases after the salt emplacement, and that shear stresses below the salt sheet are high, increasing the probability of compressional failure on the borehole wall. Overall, our results highlight that forward evolutionary modeling can improve borehole stability calculations below salt.

Technical Session 2 – California East
Hydraulic Fracture - Experiments
Monday, June 29, 2015, 08:00 am - 09:30 am
Chair: TBD

ARMA 15-0444

Injection Induced Fracturing As a Necessary Evil in Geologic CO_2 Sequestration

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The fracturing of any component of the geologic storage and containment system is generally viewed as a liability to be avoided in carbon capture and storage (CCS). Yet in large-scale CCS, injection-induced fracturing of the storage reservoir is almost a certainty. This is true even when operators keep injection pressures below the nominal fracture gradient. We examine the implications of this dilemma with several process models informed by field data.

Models and field measurements indicate that pipeline-delivered CO2 will still be relatively cool when it enters the reservoir rock. The consequent thermoelastic stress reduces the fluid pressure needed to fracture the rock at the injection well. The reduction is so large that commercial injection rates cannot be attained if fracturing is prohibited. Simple considerations show that the CO_2 does not warm significantly as it travels along the fracture, but the injection-induced fracture nevertheless propagates only a finite distance into the storage reservoir because friction within the fracture reduces the fluid pressure at the fracture tip. This prediction is consistent with field observations of injectivity.

Such self-limiting propagation is useful for increasing the overall rate of storage and need not jeopardize containment of the CO_2, especially if injection is coupled with pressure management via extraction wells. The latter assertion finds support in historical field data from waterflooded oil reservoirs, whose combination of injection and extraction wells constitute a pressure management analog. Waterflood injectivity remains large and approximately constant over long periods of time (decades) and is almost uncorrelated to reservoir permeability. These features are consistent with our model predictions. We conclude that injection induced fracturing of the storage reservoir is both inevitable and beneficial, if properly managed.

ARMA 15-0248

Integrated Experimental and Computational Study of Hydraulic Fracturing and the Use of Alternative Fracking Fluids

Hari Viswanathan[1], James Carey[2], Satish Karra[2], Mark Porter[2], Esteban Rougier[2], Robert Currier[2], Qinjun Kang[2], Lei Zhou[2], Joaquin Jimenez[2], Nataliia Makedonska[2], Li Chen[2], Jeffrey Hyman[2]
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Shale gas is an unconventional fossil energy resource that is already having a profound impact on US energy independence and is projected to last for at least 100 years. Production of methane and other hydrocarbons from low permeability shale involves hydrofracturing of rock, establishing fracture connectivity, and multiphase fluid-flow and reaction processes all of which are poorly understood. The result is inefficient extraction with many environmental concerns. A science-based capability is required to quantify the governing mesoscale fluid-solid interactions, including microstructural control of fracture patterns and the interaction of engineered fluids with hydrocarbon flow. These interactions depend on coupled thermo-hydro-mechanical-chemical (THMC) processes over scales from microns to tens of meters. Determining the key mechanisms in subsurface THMC systems has been impeded due to the lack of sophisticated experimental methods to measure fracture aperture and connectivity, multiphase permeability, and chemical exchange capacities at the high temperature, pressure, and stresses present in the subsurface. This project uses innovative high-pressure microfluidic and triaxial core flood experiments on shale to explore fracture-permeability relations and the extraction of hydrocarbon. These data are integrated with simulations including

lattice Boltzmann modeling of pore-scale processes, finite-element/discrete element models of fracture development in the near-well environment, discrete-fracture modeling of the reservoir, and system-scale models to assess the economics of alternative fracturing fluids. The ultimate goal is to make the necessary measurements to develop models that can be used to determine the reservoir operating conditions necessary to gain a degree of control over fracture generation, fluid flow, and interfacial processes over a range of subsurface conditions.

ARMA 15-0755

Flow of high solid volume fraction fluids through fractures and around obstructions

Ricardo Medina[1], Russell Detwiler[1], Romain Prioul[2], Joseph Morris[2,3], Jean Desroches[4], Alberto Ortega[5]
[1]University of California, Irvine, [2]Schlumberger-Doll Research, [3]Lawrence Livermore National Laboratory, [4]Services Pétroliers Schlumberger, [5]Schlumberger

Flow of high-concentration suspensions through fractures is important to a range of natural and induced subsurface processes where fractures provide the primary permeability (e.g., mud volcanoes, sand intrusion, and hydraulic fracturing). Flow of suspended solids through confined geometries can be affected by the solid concentration, fluid rheology, and obstructions, which may affect or redirect solid movement within the fracture. The fracture wall roughness, closed pore throats, fracture joints, asperities, reduced aperture, and dikes are all features capable of forming obstructions that may have the ability to cause jamming of these suspended solids flows. When the solids stop moving, relative to the fluid flow, a zero-velocity region (jamming region) develops where the solid concentration reaches the close packing limit and the fracture transitions to a porous media. We present results from experiments in which a high concentration (50% by volume) of granular solids suspended in a non-Newtonian carrier fluid (0.75% guar gum in water) flowed through a parallel-plate fracture with a thin, plate-like, obstruction parallel to the flow. Digital imaging and particle-image-velocimetry analysis provided detailed two-dimensional maps of velocities within the fracture. Results demonstrate development of a strongly heterogeneous velocity field within the fracture. Surprisingly, we observed the highest velocities along the no-flow boundaries of the fracture and the lowest velocities along the obstruction. The geometry and orientation of the obstruction will change in future experiments and will help better understand the development of a jammed region.

ARMA 15-0294

Laboratory measurements of flow through wellbore ceement-casing microannuli

John Stormont[1], Rashid Ahmad[1], Joshua Ellison[1], Mahmoud Taha[1], Ed Matteo[2]
[1]University of New Mexico, [2]Sandia National Laboratories

Wellbore integrity is central to ensuring permanent storage of CO_2 in geologic formations. Many wellbores are expected to leak for a variety of reasons, and the cement-casing interface has been identified as a common leakage pathway. The leakage pathway is typically conceptualized as a fracture-like flaw and therefore the leakage rate is expected to be a function of the internal pressures in the casing as well as the external or confining pressures acting on the wellbore system.
We have developed an experimental system that allows testing of seal systems comprised of a cement sheath cast on a steel casing. The seal systems are 20 cm long, and have an outer (cement) diameter of 10 cm and an inner (steel casing) diameter of 5 cm. The samples are cast using Type G cement. Samples were produced with a range of flaws, including a microannulus between the steel casing and the cement and fractures in the cement. The system allows independent application of confining pressures to 20 MPa and internal (casing) pressures to 14 MPa. The longitudinal permeability of the seal system can be measured by means of gas accessible to the top and bottom of the seal systems using steady-state and/or transient measurements.
We present results in terms of the effective permeability of various flaws in seal systems as a function of confining pressure, internal pressure and pore pressure. We further interpret the measurements in terms of the size and compressibility of the flow paths.

ARMA 15-0065

True-Triaxial Hydraulic Fracturing of Niobrara Carbonate Rock as an Analogue for Complex Oil and Gas Reservoir Stimulation

Luke Frash[1], Marte Gutierrez[1,2], Azra Tutuncu[1], John Hood[1], Mehdi Mohktari[1]
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Well stimulation by hydraulic fracturing is a common method for increasing the injectivity and productivity of wells. This method is beneficial for many applications including oil, gas, geothermal energy and CO_2 sequestration, however hydraulic fracturing in shale formations is still poorly understood. Fractures created by hydraulic fracturing are expected to interact with the reservoir rock structure to produce complex fracture networks. Fracture complexity with branching and intersection of natural discontinuities has the potential increase production from wells. On the contrary, tortuous and stranded fractures can reduce hydraulic conductivity of individual fractures relative to simplified models. A 300x300x300 mm^3 block specimen of Fort Hays Limestone was hydraulically fractured in the laboratory using a true-triaxial apparatus to study complex hydraulic fracturing. This material is a member of the Niobrara Shale formation, a major unconventional oil and gas play in the Denver-Julesburg Basin. Hydraulic fractures were stimulated by injection of plastic epoxy. This injection fluid permitted viscosity controlled fracture growth and aided post-stimulation study of the stimulated fracture network geometry. The injected epoxy exhibited a secondary benefit of clearly marking the fluid penetrated zones of the stimulated fractures, preserving the in-situ fracture aperture and bonding the fracture faces to give improved visualization of complex fractures in cross-sections cut after the experiment. This experiment resulted with a complex fracture network including prominent tensile hydraulic fractures, shear activated discontinuities and bedding plane separations. Acoustic emissions, injection pressures and injection rates were analyzed with reference to the fracture geometry to develop relationships between these parameters and to develop means of identifying complex fracture growth, as applicable in field scenarios where the actual fracture geometry is not easily measured.
Keywords: Hydraulic fracture, Niobrara Shale, complex fracture network, stimulated reservoir volume

ARMA 15-0662

Proppant Transport at the Fracture Scale: Simulation and Experiment

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Laboratory and field studies have demonstrated a strong correlation between the volume of proppant deployed in hydraulic fracturing operations and subsequent reservoir productivity. In recent years, the desire to improve proppant performance has led to the development of new generations of exotic proppants, as well as new propping strategies. Nevertheless, the factors controlling performance of even traditional proppants in real rock fractures are poorly understood. Improved models are needed to help devise optimal strategies for deploying traditional and new varieties of proppant.

Large-scale proppant models frequently rely on empirical closure relationships to represent real-world transport behavior. However, care must be taken when applying such relationships outside their derived context. In particular, most models employ closure relationships determined for slurries where the fluid dimensions vastly exceed the particle size. This is not true for fracture flow, where wall effects alter the effective transport properties and introduce new interaction forces.

This presentation describes an ongoing study employing a combination of high fidelity numerical simulations and fracture-scale experiments to describe the transport properties of proppant particles in fractures. The experimental work examines proppant movement in clear-plastic three-dimensional reproductions of the shale surfaces recreated using three dimensional printing. These specially tailored flow cells are used in combination with micro-capsules with tunable density and opacity for improved particle tracking in dense particle packs. The same shale surfaces are also employed in

high-resolution particulate flow simulations in which both the particles and interstitial fluid motion are explicitly represented. The data gathered from these experiments and simulations are used to help constrain models of settling and dispersion in particle-laden fluids within fractures.

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Technical Session 3 – Elizabethan AB
Laboratory and Field Testing

Monday, June 29, 2015, 08:00 am - 09:30 am

Chairs: Qing Lin & Joseph Labuz

ARMA 15-0629

Recent Tests and Large Excavations in Underground Research Laboratories and Facilities

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Since the formation of the International Society for Rock Mechanics (ISRM) Commission on Underground Research Laboratory (URL) Networking in 2011, we have attended and organized URL-related meetings. During 2013 -2014, the gatherings of Commissioners include the 3rd SINOROCK, 47th ARMA symposium, 13th TAUP (Topics in Astroparticle and Underground Physics) conference, 2013 AGU annual fall meeting, 2013 EUROCK symposium, 4th iDUST (inter-Disciplinary Underground Science and Technology) conference, and the 8th ARMS (Asia Rock Mechanics Symposium). The 2015 planned activities include the 4th URL workshop associated with the 13th ISRM Congress. Recent progress in planned heater tests in radioactive waste URLs, designs of large excavations in deep physics facilities, and other underground studies are reviewed in this article. Rock mechanics findings and multi-disciplinary studies are among topics of interest to the ISRM Commission. Heater tests for better understanding of the coupled thermal-hydro-mechanical-chemical processes are of interest to radioactive repository assessments and for other thermal storage and geothermal production projects. Large excavations in physics laboratories are driven by the needs associated with designing next generation of experiments to detect rare events. Some existing physics laboratories are interested to use available spaces for geo-sciences studies, including microbiological research for deep life. We review the progress in these topics and welcome inputs on case histories and planned developments in URLs. The inputs from the geo-engineering and rock mechanics communities are essential for our continuing efforts of the ISRM URL Networking Commission.

ARMA 15-0532

Long-term creep experiments on Haynesville shale rocks

Fatemeh Rassouli[1], Mark Zoback[1]
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Shales with high clay and carbonate content show significant variations of physical behavior under different conditions of stress and temperature, which can affect the mechanical and fluid flow properties of reservoir rocks. In this study, we present two types of creep experiments, time-cycling triaxial deformation and uniaxial indentation creep tests conducted on three samples from the Haynesville formation in east Texas.

Triaxial experiments were performed in a time-cycling pattern that includes a series of multi-stage loading/creep/unloading/recovery experiments at different time spans. The main goal of these experiments was to study creep in both relatively short term (several hours) and long term (several weeks) experiments. All creep stages of these experimental were performed at a constant differential stress level, varying only the testing time of each creep/recovery stage. Experiments were done on both horizontal and vertical shale samples to address anisotropy introduced by the bedding.

The indentation experiments were performed on a single horizontal shale sample, for only few hours using a 2 mm diameter flat-ended indenter. The main purpose of conducting indentation experiments was to investigate the possibility of measuring creep parameters of bulk samples on a small scale in a relatively simple apparatus.
A power-law (Equation 1) model was fit to all creep measurements to find the constitutive parameters of the time-dependent deformation of the Haynesville shale samples.

$$\varepsilon = \sigma B t^{n}, \qquad (1)$$

where ε is strain, σ is the applied differential stress, *t* is time, *n* is the power-law exponent and the remaining parameters are constant constitutive parameters.
Although the creep compliance response of the horizontal sample is higher in the indentation experiments than in the triaxial creep tests, all *n* values from both experimental techniques range between 0.25 and 0.52. The *B* values for the horizontal sample in indentation experiments, 0.3 e-6 MPa^{-1} to 1.3 e-6 MPa^{-1}, are comparable with the ones for the vertical sample in triaxial experiments, 2.04 e-7 MPa^{-1} to 1.4e-6 MPa^{-1}, while the *B* values for the horizontal sample in triaxial experiments are the lowest 3.95 e-8 MPa^{-1} to 9.12 e-8 MPa^{-1}. The higher deformation of the vertical sample can be explained by mechanical compaction processes like crack closure in rocks.
The preliminary results of this study highlight the potential for using indentation creep tests performed in only a few hours, on a small volume of rock to predict the time-dependent deformation of shales. Although further experiments are needed to analyze the difference between indentation and triaxial test results, both experimental techniques show that the few-hours creep tests are able to provide constitutive parameters for power-law creep model for long-term deformation of shales.

ARMA 15-0168

Performance of Drilled Shafts Socketed in the Dead Sea Crystalline Salt under Short Term Vertical Loading Condition

Ayman Fayed[1]
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Drilled shafts socketed in crystalline salt are a common type of foundations used in the Dead Sea region to support high vertical and lateral loads. The existing subsurface condition consists of soft clay followed by crystalline salt. Due to the difference in nature and formation creation method, the performance of such foundation type under vertical loading in the crystalline salt is different from their commonly known behavior in rock. This paper is an attempt to understand the real behavior of socketed drilled shafts in crystalline salt through a finite element modeling of an actual pile load test carried out in this formation. The studied condition is a steel tubular pile provided with a reinforced concrete socket in the salt formation. The prevailing salt layers in the pile test area are highly fractured crystalline rock salts of variable strength ranging from weak to moderately weak.
Full details of the pile load test, description of the subsurface conditions and salt strength tests are presented in this paper with the finite element analysis details and results. The developed shear resistance along the socketed length of the pile is verified and compared to the commonly used relations and values for the common rock formations. The performed analyses and comparison with the pile load test results provided a better understanding and good information about the drilled shaft performance under vertical loading in such formation.

ARMA 15-0666

Innovative *In Situ* Stress Testing Using Unconventional Equipment and Procedures for High-Pressure Hydropower Tunnels

Peter Dickson[1], Masrour Kizilbash[1], John Young[1]
[1]*MWH*

In planning, design, and construction of high pressure water tunnel systems, a critical issue is knowing the ability of *in situ* stress conditions in the rock mass to provide sufficient confinement to prevent leakage of high-pressure water. If confinement is inadequate because of insufficiently high rock stresses, there is the potential for hydraulic jacking or hydraulic fracturing to occur. Where such conditions are found, or where excessive leakage into the rock mass must be minimized, such as in the vicinity of an underground powerhouse or a valley side, an impermeable lining system is required. Typically, this is provided by expensive steel-lining. For these reasons, considerable importance is placed during site investigations and characterization on obtaining reliable information about rock stresses needed for selection of an appropriate and safe lining system.
Field investigations are designed to determine actual *in situ* stresses or to verify that are in accordance with expectations from regional conditions or preliminary rock cover estimations. Various methods are commonly used, including standardized hydraulic fracturing methods, hydraulic jacking testing, and over-coring. Experience has shown that with each of these methods there are limitations in being able to provide reliable data in a cost effective and efficient way. In addition to unique site geologic conditions sometimes complicating or prohibiting data collection, the cost of conducting certain methods has resulted in insufficient numbers of tests being performed to develop properly representative interpretations and design solutions. This is exacerbated by the small number of experienced experts qualified to do such investigations, especially when projects are located in developing countries.
A modified approach of hydrojacking testing is described that has been used successfully on hydropower projects in the Himalayas and Andes where other more traditional methods had been unproductive. The method involves use of water pressure test and grouting equipment and resources generally available in-country or already under contract on a construction project, without engaging specialist contractors from Europe or North America, although supervision and interpretation by experienced individuals is still needed. The lower cost and rapidity of testing permits more data to be collected than would otherwise be achieved (especially for remote sites in developing regions), with better representation of the range geologic conditions associated with hydraulic jacking, characterization of differences between local or global stress deficiencies, and development of an improved understanding of how such conditions can be treated. This paper also describes successful case history experiences of this method that is becoming more and more commonplace but which possibly suffers from not being sufficiently recognized in North America or properly standardized to gain universal acceptance.

ARMA 15-0148

Nanoindentation Creep Measurements on Shale

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Creep is a term used to describe the time dependent behavior of rock. Knowledge of creep can be used to predict the reservoir subsidence associated with production, wellbore stability and also proppant embedment. In this work, we investigate creep behavior at small scale using Nanoindentation. After the initial nanoindentation loading stage, the indenter tip is held under constant maximum force for a period of time and we record the deformation. The measured creep values are compared for different materials including fused silica, Lyons sandstone, Sioux quartzite, pyrophyllite, and Indiana limestone. The measurements on shales are then presented. The experiments measure comparably higher creep values for shale, i.e. 10 times higher than fused silica. This creep depends strongly on porosity and mineralogy. TOC and clay content correlate positively with creep, while carbonate content correlates negatively with the creep. The measurements reveal a directionally dependent (anisotropic) creep with a higher value in the direction perpendicular to the bedding. Measurements also show capability to derive the creep compliance coefficients. Mercury Injection Capillary Pressure (MICP) and acoustic velocity measurements are correlated with this compliance. The measured creep compliance could be an indicator of the volume of smaller pore sizes (nanometer scale) which are found in the organic and clay components.

ARMA 15-0639

Investigation into the Effect of Length to Diameter Ratio on the Point Load Strength Index of Gosford Sandstone

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Since the introduction of the point load test a size effect has been observed in the point load strength index. While considerable research has been undertaken to investigate the size effect in the point load strength index, and the general cause of size effect, there has been limited research applying size effect theories to the size effect observed in the point load strength index. This paper investigates the applicability of size effect models including Size Effect Law (SEL), Multifractal Scaling Law (MFSL) and the Brook model to both the axial and diametral point load strength index at varying sample length to diameter ratios. In addition, the size effect at varying length to diameter ratios of a point load strength index which incorporates the contact area between the point load pointer and sample has also been investigated.

Through an experimental investigation of both axial and diametral point load tests involving over 275 samples of Gosford sandstone this investigation found that the point load strength index decreases as sample diameter increases for all investigated sample length to diameter ratios. The SEL and MFSL size effect models best fitted to the size effect trend of Gosford sandstone axial point load strength index. The point load strength index incorporating contact area was found to increase as the sample diameter increased for all investigated length to diameter ratios. The FFSEL size effect accurately modelled the increasing Gosford sandstone point load strength index for both axial and diametral results and across all length to diameter ratios.

Technical Session 4 – Elizabethan CD
Mining Induced Seismicity and Rock Bursts
Monday, June 29, 2015, 08:00 am - 09:30 am
Chairs: Kim McCarter & Peter Swanson

ARMA 15-0169

Rock-burst simulations with 2D-DDA

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[1] *Ben Gurion University of the Negev,* [2] *Institute of Rock and Soil Mechanics, Chinese Academy of Sciences*

Rock-bursts can be defined as a sudden displacement of rock in deep excavations that can come in different intensities and may cause severe damage in life and equipment. Two source mechanisms are typically considered for rock-bursts: 1) Strain relaxation leading to displacement of excavation surfaces, 2) Energy redistribution induced by explosions and drilling activity at the working face. In this study we investigate further into those mechanisms using the numerical Discontinuous Deformation Analysis (DDA) method.

DDA is a numerical, discrete element method, which solves a more general type of a finite element mesh. By using a new viscous boundary and excavation sequence modeling capabilities we now have the ability to model dynamic deformation during deep tunneling excavations at higher accuracy. The rock-burst type considered here is slip-fault based, because the DDA version we are using only solves for large block displacements along preexisting discontinuities; fracture mechanics and excavation induced fracture are not considered.

To verify the accuracy of the DDA wave propagation in a discontinuous medium, a simulation of P-wave in one-dimension elastic bar was performed. The results show that DDA presents high accuracy provided that the time step is sufficiently small and the ratio between block and wave lengths is between 1/8 and 1/12. Additionally, a radial P-wave propagation simulation was formed to emulate an underground blast. Finally, a simulation of a blast functioning as a micro seismic event

in a discontinuous medium with an open tunnel was compared to in-situ measurements made in the Jinping II Hydropower project in Sichuan province, China.
After performing the validations successfully we began modeling the strain relaxation mechanism by removing circular tunnel sections in a medium subjected to increasing levels of hydrostatic stresses from 0 to 50 MPa and monitored the behavior of keyblocks around the tunnel. We obtained a very strong relation between the initial stress and the velocity and acceleration of the ejected key block following the removal of the tunnel section, which gives an indication regarding the intensity of the predicted event as a function of the level of initial in-situ stress and the geometrical and mechanical characteristics of the jointed domain.

We are now exploring the energy redistribution mechanism due to a faraway blast.

ARMA 15-0254

Contribution of shear slip in a widespread compressive pillar failure

Eric Poeck[1], Ryan Garvey[1], Kun Zhang[1], Ugur Ozbay[1]
[1]*Colorado School of Mines*

A release of energy occurs during mining-related seismic events such as rock bursts and coal bumps. The magnitude of these events depends partly upon the energy available in the loading system and partly upon the post-peak softening behavior of the failing medium. In addition, the extent of unstable failure and associated release of energy can be affected by slip along interfaces between dissimilar materials. This paper compares the results of two numerical models from the back analysis of a coal mine collapse that resulted in a 3.9 local magnitude seismic event. Release of kinetic energy is considered in the simulations, which were run using a 2D distinct element software package. The models differ in that the interfaces between the coal and the surrounding rock are defined either through Coulomb slip joint parameters or continuously yielding (displacement-softening) joint parameters. The geometry, loading conditions, and mining sequence are otherwise identical. The coal is modeled as a strain-softening material, and the roof and floor are modeled as continuous elastic blocks. The failure response and magnitude of released energy are compared between the two models. The results of the analysis indicate that the softening interface parameters between the coal and rock facilitate a widespread collapse and lead to a release of energy more than one order of magnitude higher.

ARMA 15-0374

Use of Micro-Seismic Monitoring Data as an Aid to Rock Mechanics Decision Making and Mine Design Verification

Brad Simser[1], Rick Deredin[1], Ali Jalbout[1], Tony Butler[2]
[1]*Sudbury Integrated Nickel Operations, A Glencore Company,* [2]*ESG Solutions*

Case studies are presented from Glencores' Fraser Copper and Nickel Rim South Mines showing how micro-seismic monitoring data can be used as an aid to rock mechanics decision making and design verification.
The Fraser Copper Mine is a narrow vein deposit using a mixture of mining methods. Most of the historic production has been mined with overhand cut and fill. The vein orientation can be erratic with an overall dip of 45^0 but local rolls going from horizontal to vertical. The steeper veins are usually extracted with blasthole methods, especially in sill pillar areas. Flat veins are mined with drift and fill methods. High stress remnant extraction of intermediate dipping veins has proven to be a significant challenge. The squat nature of the narrow vein sill pillar can hold very high stress until very late stages of extraction. A case history showing the performance of a planned underhand extraction of a highly stressed remnant is given. Face bursting necessitated a change of the mining plan, and a successful long hole destress blast was conducted. The performance of the destress blast as well as the overall rockmass response to mining in this area is shown using micro-seismic data and underground observations.
Nickel Rim South mine is a primary/secondary blasthole mine which is relatively deep (1100 to 1710m below surface) with horizontal stresses approximately 1.6 times vertical. The mine has a

complex system of faulting and variable geology, but generally high quality rock. A dense micro-seismic array was installed early in the mine life. Examples of how recorded development blasts can be used to quickly evaluate source location accuracy and infer the state of rockmass conditions are given. A case is made for 3D velocity models and recognizing the impact of waveform attenuation from raypath effects, and yielded rockmass conditions. Examples of how network sensitivity can enhance the understanding of the rockmass response to mining are also presented.

ARMA 15-0394

Induced Microseismic Monitoring in Salt Caverns

Zara Hosseini[1], David Collins[1], Ian Pinnock[1], Vladimir Shumila[1], Cezar Trifu[1]
[1]*ESG Solutions*

Induced Microseismic Monitoring in Salt Type Rocks
The use of induced microseismic monitoring has advanced significantly over the past few decades due to developments in technology and the applications of microseismic data in fields other than hard rock mining.
Investigation of mechanisms and source parameters of seismic data and incorporating into geotechnical analysis has resulted in growing applications of microseismic monitoring in mining, geotechnical and petroleum fields.
This paper aims to review the prospects and challenges of microseismic monitoring in soft rock material such as coal, potash and salt.
Two cases of in-flow monitoring in one operation and salt cavern monitoring in another site are demonstrated in this paper and system configurations and data quality are discussed.
The results show that even though waveform attenuation and surface noise remain a challenge for this type of media, the recorded seismicity and the analysis of source parameters can provide an insight into the rockmass changes, fluid movement and potential signal for cavern/opening instability.

ARMA 15-0650

Rock burst of underground pillars

Omid Hosseini[1], Roosevelt Theodore[1], Mehrdad Razavi[1], Ali Fakhimi[1]
[1]*New Mexico Tech*

Rock burst is a spontaneous and uncontrolled failure of brittle rock structures. As a result of rock burst in a pillar, in a very short period of time, the apparently statically deforming rock can turn into the dynamic deformation and violent failure. Consequently, rock particles can be ejected with a velocity of 8 to 50 m/s (Ortlepp, 1993) which can cause fatal injuries and damages to the equipment. In this study, rock burst in underground pillars is studied by conducting physical tests on cylindrical rock specimens of Pennsylvania blue sandstone. To mimic the elasticity and energy absorption of the roof system, a steel frame was designed and used to apply the load to the specimen; the rock specimen was loaded under stroke control through the steel frame. Violent failure was observed and rock particles ejection velocities of up to 4 m/s were measured using a high speed camera. To simulate the physical tests, a three-dimensional bonded particle model (BPM) was used. The BPM was calibrated to mimic the mechanical properties of the sandstone. The steel frame was discretized to finite elements and assumed to be linearly elastic. The physical and numerical steel frames are shown in Fig. 1. The damaged specimens, for the situations without and with friction between the rock and the loading platens, are shown in Fig. 2. The variation of the specimen kinetic energy versus the axial strain in Fig. 3 clearly shows the violent nature of the specimen failure. High particle velocities of a few meters per second were observed in the numerical simulations. The effect of several parameters including the specimen aspect ratio, the lateral specimen confinement, and the loading frame stiffness on the severity of the rock failure and induced kinetic energy will be addressed in this study.

References
Ortlepp, W.D. (1993), High ground displacement velocities associated with rock burst damage, Rock burst and seismicity in mines, Young, R.P. (ed.), A.A. Balkema, pp. 101-106.

ARMA 15-0849

The Technology and Practice of Rockburst Prevention in Chinese Deep Coal Mine

Qingxin Qi[1], Junliang Li[1], Yu Ning[1], Zhenhua Ouyang[1], Shankun Zhao[1], Wei Like[1]
[1]*China Coal Research Institute*

In China, rockbursts and the secondary disasters have been associated with thousands of accidents and casualties in nearly 140 coal mines in the past 40 years. Rockburst has become one of the major dynamic disasters threatening deep coal mining. Departments of safety supervision and administration, research institutes and coal production enterprises paid more and more attention to rockburst in the recently years. Through revising "coal mine safety regulations" and formulating other normative documents, more strict requirements were put forward by the departments of safety supervision and administration from hazard assessment, rockbursts monitoring, regional precaution, locality prevention, effect test and security protection. Some science researchers from institutes and universities focused their studies on the mechanism of rockburst, and them recognized that the essence of rockburst was the abrupt destruction of coal rock mass after its bearing capacity exceeded the compressive or shear strength. Based on the stress control theory, a series of rockburst prevention methods were applied in coal mine in China. In detail, optimized mining layout, exploited protective layer and other regional stress control methods were applied to fundamentally change the occurred conditions of rockburst. And broken roof pre-splitting blasting, unloading of coal seam burst, coal, seam, water, injection, large diameter pressure relief, broken floor blasting and other local stress control methods were applied to remove the heavily stress concentration which maybe induced rockburst in coal rock mass.

Technical Session 5 – California West Injection & Caprcok

Monday, June 29, 2015, 11:00 am - 12:30 pm

Chairs: Nicholas Thompson & Sander Hol

ARMA 15-0331

Mechanical testing and sealing capacity of the Upper Jurassic Draupne Formation, North Sea

Elin Skurtveit[1], Lars Grande[1], Oluwakemi Y. Ogebule[2], Roy H. Gabrielsen[2], Jan Inge Faleide[2], Nazmul H. Mondol[1,2], Rudolf Maurer[3], Per Horsrud[3]
[1]*Norwegian Geotechnical Institute,* [2]*University of Oslo,* [3]*Statoil ASA*

Although cap rock integrity is one of the key issues for safe CO_2 storage, high quality shale samples for mechanical characterization and geomechanical evaluation of cap rock is sparse. Recently, nine meters of shale allocated for research on cap rock integrity was cored in the Upper Jurassic Draupne Formation, in the southern North Sea. The coring and sampling process was closely monitored to ensure that intact samples and the core where immediately emerged in oil and sealed to avoid drying and changes of basal rock mechanical properties.
The core depth is from 2574.5 m to 2583.5 m. The uppermost meter and the lowermost two meters of the 133 mm diameter core have so far been opened. Inspection of core sections show a homogeneous black shale with Mode I unloading fractures with approximately 10-40 cm spacing. In the upper core section, a Mode II shear fracture with horizontal striation on a polished surface is observed. The very top of the upper core is a rubble zone, which has a conical contact delineated by a hybrid Mode III fracture surface. The intact shale of this zone show clear evidence of a drilling-induced failure, with the surface sculptured by intense rotation. The rubble zone possesses fragments of reddish and yellowish silty material. Although the rubble zone was clearly formed during drilling,

the failure in this zone was most likely produced by shearing along a primary lithological boundary (mudstone/silt).
The planned mechanical test program includes general geomechanical and mineralogical characterization, including the determination of shear strength and stiffness, tensile strength. In addition, K0 and oedometer consolidation focusing on shale anisotropy and rock physical measurements like sonic velocity and resistivity will be included. Preliminary results, documents a low-permeable shale with permeability in the range of 1-5x10^{-7}mD. The higher permeability is in the horizontal direction. Triaxial test (using the procedure of Berre 2011) was performed for consolidation stresses of 5 and 20 MPa, after saturating the samples with brine with the same NaCl content as the pore fluid. Undrained maximum shear strength was found to be in the range of 18-35 MPa and shows some anisotropy with a slightly higher strength for the horizontal plugs (plug axis parallel with bedding plane) compared to the vertical plugs (plug axis normal to bedding plane), whereas plugs with oblique angle to the bedding is characterized by the lower strength.
Detailed mechanical testing and evaluation of high-quality shale cores from the Draupne Formation are an important input to further geomechanical modelling of cap rock integrity and fracture pressure, and will presumably provide a significant contribution for the further development of CO_2 storage potential in the North Sea.

ARMA 15-0352

A finite element geomechanical study of the brittle failure of a caprock due to deflation

Thibaut Defoort[1], Saeed Salimzadeh[1], Adriana Paluszny[1], Robert W. Zimmerman[1]
[1]*Imperial College*

The deformation of an initially intact caprock, caused by the swelling of an underlying reservoir during CO_2 injection, is geomechanically modeled in three dimensions using damage and fracture models. The objective is to evaluate the effect of pre-existing damage generated during deflation, on the localization of further damage and initiation of fracture during re-injection. As a result of deformation, damage accumulates at stress concentration regions, and pre-conditions fracture growth and permeability predictions. An isotropic damage model accounts for micro-fracture growth in response to the accumulation of tensile elastic strain. Damage is evaluated as a precursor to fracture, which can decrease caprock integrity and locally enhance permeability. Fractures are represented explicitly in the mesh, and stress intensity factors at fracture tips are computed using I-Integral solved using the reduced virtual integration approach. Stress intensity factors are used as a predictor of growth under both tension and compression. The caprock is assumed to be at 3,800 m depth with overburden stresses of 90 MPa. It is modeled as a 50m thick layer lying on top of a 100m sandstone reservoir; with an upscaled Young's modulus of 5 GPa and Poisson's ratio of 0.25. Deflation and re-inflation is modeled as a volumetric strain boundary condition caused by the progressive deformation of the underlying reservoir. Modelling the reservoir allows for indirect definition of the displacement boundary conditions of the caprock. We model three scenarios: deflation only, inflation only, and re-inflation followed by deflation. The first two assume that the caprock is initially undamaged, while the second assumes that deflation preconditions the caprock and creates damage that can potentially aggravate during re-inflation. The influence of the mesh size is evaluated, and the damage parameters are examined in relation to element size. A comparative study provides insight into the relative importance of modelling damage in the context of fracture growth for loading conditions of deflation followed by re-inflation. Maximum predicted stress concentrations are varied for different levels of heterogeneities including a matrix which is isotropic and homogeneous, a matrix with varying toughness and elasticity moduli, and a matrix with a low density fracture population.

ARMA 15-0364

Qualifying Stress Direction from Borehole Shear Sonic Anisotropy

J Donald[1], Erik Wielemaker[1], Florian Karpfinger[1], Francisco Gomez[1], Xinyu Liang[1], Mark Tingay[2]

[1]*Schlumberger*, [2]*University of Adelaide*

Identifying stress direction using borehole measurements is today commonly achieved through the acquisition and interpretation of borehole image logs, oriented calipers and shear sonic anisotropy logs. The shear sonic anisotropy technique is commonly used in the petroleum industry for complimenting other methods, such as borehole failure measured from calipers and images, to deduce the direction and magnitude of the present-day horizontal stresses. In environments where the rocks are stress-sensitive, acoustics methods suitable to this type of lithology are often the only indication for stress imbalance and direction. Borehole failure methods for determining stress direction and magnitudes using images can be problematic in sediments that are considered plastic or in boreholes that may not exhibit any failure, which is becoming more common with oil based mud systems. In this paper we will review how stress directions and magnitudes can be derived from shear anisotropy logs.

Shear anisotropy can be quantified as the Borehole flexural waves will polarize in a Fast and Slow shear wave. Borehole acoustic (flexural) waves respond to differential horizontal stresses in stress sensitive formations. In order to identify such zones, slowness-dispersion analysis is used. Differential horizontal stresses can be identified using dispersion analysis by its characteristic cross-over signature of the fast and slow dipole flexural wave data in near-vertical boreholes. Understanding of the cross-dipole sonic measurements using dispersion analysis enables the diagnosis of the dominant type of anisotropy present in the formation by examining the slowness-frequency response of the naturally dispersive flexural wave. Interpretation of borehole dipole flexural acoustic waves is also used to identify other dominant anisotropy mechanisms such as shale layering and open natural fractures. Although sonic anisotropy and slowness dispersion analysis has been well documented and used in the petroleum industry, there is a need to clarify how one can qualify whether the observed anisotropy is due to stress, and not influenced by borehole conditions or by other sources. Measurements of oriented four-arm caliper data and borehole image data (electrical, induction or ultrasonic) have been widely used to relate borehole elongation, shape, and failure to magnitude and direction of in-situ horizontal stresses. Guidelines and criteria for interpreting caliper and image data specifically for identifying stress induced features are well documented to provide both a quality check and consistency of interpretation.

This paper describes (1) a set of guidelines for the use of slowness-dispersion analysis to identify stress induced anisotropy from other types of anisotropy, (2) a quality ranking scheme for quantifying results of stress direction in order to compare to other methods for identifying borehole stress features, and (3) review of methods for determining stress magnitude using borehole acoustic waves in vertical wellbores. Case studies from petroleum reservoirs on land and offshore are presented illustrating these concepts.

ARMA 15-0112

APPLICATION OF ANALYTICAL PROBABILISTIC METHOD TO ESTIMATE MINIMUM HORIZONTAL IN SITU STRESS FROMA LEAK-OFF TEST (LOT) ACQUIRED IN A HIGH INCLINED WELL IN A DEEPWATER TURBIDITES OIL FIELD, OFFSHORE BRASIL

Miguel Galarraga[1]

[1]*Shell Brasil Petroleo Ltda*

Typically is assumed that the maximum horizontal in situ stress is the average between the overburden and minimum horizontal in situ stresses in normal faulting regime environment, and rock mechanics properties derived from single or few wells control points provide a good representation across the field with respect to borehole stability studies. However, the uncertainties associated with these assumptions are generally not considered.

The paper presents an analytical probabilistic approach using Monte Carlo Simulation method to estimate the minimum horizontal in situ stress magnitude from a single Leak-off test (LOT) acquired in highly deviated well in a sand interval inside the reservoir section, accounting for the uncertainties in some of the key input variables such as maximum horizontal in situ stress magnitude, and rock mechanic properties (Young Modulus, and Poisson's Ratio). The major assumption used is that the Leak-off test (LOT) acquired was a representation of the fracture initiation pressure in the sand interval. A field case in a deep water turbidites oil field located offshore Brasil is presented to illustrate the application of this approach.

The result of this study provides a full probabilistic density function (PDF) for the estimated minimum horizontal in situ stress magnitude.

Estimation of the minimum horizontal in situ stress in the overlying cap rock from an extended leak-off test (XLOT) was available before initiating this study, which combined with the results obtained in this piece of work indicated that the minimum horizontal in situ stress contrast between the reservoir and the overlying cap rock is relative small in any cases as expected in shallow and unconsolidated sediment environment. The outcome of this study was used to help define the operational envelope during the water injection in the field.

ARMA 15-0305

Numerical model of extended leak-off test (XLOT)

Andreas Bauer[1], Idar Larsen[1], Alexandre Lavrov[1]
[1]*SINTEF Petroleum Research*

Extended leak-off test (XLOT) is one of the few in-situ stress measurement methods available in oil and gas industry. When an interval has been drilled and cased, a short section (3-5 m) is drilled forward, thereby exposing the formation. Fluid is then injected so as to induce a fracture, similar to hydraulic fracturing used in well stimulation. The difference between XLOT and hydraulic fracturing is that the height and length of the fracture produced in the former are 1 to 2 orders of magnitude smaller than in the latter. After the fracture has been created and driven just outside the near-well area, the well is shut in; the well is then opened and the fluid is bled off from the fracture into the well. After the flow-back, one or more repeat injection cycles are performed.

Different techniques have been proposed for interpreting XLOT. In particular, it has been conjectured from field tests and simple models that an inflexion in the flow-back pressure *vs* time curve occurs when the wellbore pressure becomes equal to the minimum in-situ stress [1]. Models currently used in the industry for the interpretation of XLOT are typically 2D, allow only for fracture growth in a pre-defined plane, and do not take into account the important role of heterogeneity in mechanical and hydraulic properties. Modeling XLOT (and hydraulic fracturing) in low-permeability formations remains a challenge in petroleum-related rock mechanics. Correct interpretation of XLOT in real, heterogeneous rocks, requires better models than currently used in the industry.

The objectives of our work were:

to develop a model of XLOT that would allow for fracture development in a heterogeneous rock, and would not require a pre-defined fracture plane;

to reproduce pressure *vs* time curves for XLOT in a low-permeability rock;

to verify if the current interpretation practices of XLOT are justified.

A hybrid finite-element / discrete-element code MDEM was used to model fracture initiation and growth. The code was coupled to the commercial reservoir simulator TOUGH2 to provide an explicit two-way coupling. An example of pressure *vs* time curve obtained in an XLOT simulation with MDEM / TOUGH2 is shown in Figure 1. The simulations confirmed that the inflexion in the flow-back curve known from field studies indeed can be used to evaluate the minimum in-situ stress. The results pave the way for better interpretation of XLOT in sedimentary rocks.

ARMA 15-0843

In Situ Stress Measurements during Well Abandonment

Alvin Chan[1]

[1] *Shell*

Produced water reinjection, waterflood, CO_2 injection and gas injection have become essential components for most field developments around the world. Integrity of the cap rock is one of the biggest safety concerns for the successful execution of these secondary recovery methods. As a result, defining a robust operation guideline that achieves maximum injection pressure/rate while preventing out-of-zone injection has become a critical geomechanics challenge. The injection limits are typically set based on the magnitude of the estimated in situ minimum stress in the cap rock derived from models that are calibrated to available direct or indirect field measurements. Traditionally, stress measurements are acquired as part of drilling operations to pressure test casing shoes. However, availability of high quality data in deepwater are very limited because of various operational constraints and concerns over weakening and damaging of the well and the formation. To address these challenges, we shifted our data acquisition strategy focus from drilling to well abandonment operations. This shift in focus provides us unique opportunities to acquire high quality measurements directly in the zone of interest without risking the integrity of the well or the cap rocks. One of the key advantages of this acquisition strategy is the flexibility and variety of tests that can be performed. The frequency and location of tests can also be tailored to different operations throughout our assets (e.g., open-hole pilot well abandonment during exploration phase vs. cased-hole development well abandonment during recompletion). With this new acquisition strategy, we can acquire measurements of in situ stress throughout the full life-cycle of the field. In this paper, we intend to highlight several examples to demonstrate how we have successfully integrated and utilized this new data acquisition program throughout Shell deepwater portfolios.

Technical Session 6 – California East Hydraulic Fracture - Modeling

Monday, June 29, 2015, 11:00 am - 12:30 pm

Chair: TBD

ARMA 15-0870

Crack Band Approach to Model 3D Hydraulic Fracturing of Gas Shale Stratum

Zdenek Bazant[1], Viet Chau[1], Y Su[1], M Salviato[1]

[1] *Northwestern University*

The recent advances in hydraulic fracturing of oil and gas bearing rocks, aka "fracking”, have been nothing less than astonishing. However, several aspects of shale fracking such as the topology, geometry, and evolution of the crack system remain not yet understood. In this contribution, based on the known shale permeability, on the known percentage of gas extraction from shale stratum, and on two key features of the measured gas outflow which are (1) the time to peak flux and (2) the halftime of flux decay, it is shown that the fracturing process is characterized by a very dense crack system, with crack spacing of only about 0.1 m. Then, a multi-physics approach to 3D modeling of fluid-driven propagation of a vast network of cracks and open joints in shale is presented. The complex nonlinear and anisotropic mechanical behavior of shale is captured by means of a microplane model. Because the crack spacing must be only about 10 cm, the fracture of shale is analyzed as a softening damage, in a smeared way, by the crack band model. 3D nonlinear equations governing the flow of compressible cracking fluid through the cracks whose opening and length is controlled by fracture mechanics are formulated.

ARMA 15-0556

Comparison of Injection-Induced Fault Reactivation and Seismicity in CO_2 Sequestration and Shale-gas Fracturing

Jonny Rutqvist[1], Antonio Rinaldi[1], Frederic Cappa[1]
[1]Lawrence Berkeley Naional Laboratory

The potential for fault reactivation and induced seismicity are issues of concern related to both geologic CO_2 sequestration and shale-gas fracturing. It is well known that underground injection may cause induced seismicity depending on site-specific conditions, such a stress and rock properties and injection parameters. To date no sizeable seismic event that could be felt by the local population has been documented associated with CO_2 sequestration activities. In the case of shale-gas fracturing, only three cases of felt seismicity have been documented out of hundreds of thousands of hydraulic fracturing stimulation stages. In this paper we summarize and review numerical simulations of injection-induced fault reactivation and induced seismicity associated with both underground CO_2 injection and hydraulic fracturing of shale-gas reservoirs. The simulations were conducted with TOUGH-FLAC, a simulator for coupled multiphase flow and geomechanical modeling. In this case we employed both 2D and 3D models with an explicit representation of a fault. A strain softening Mohr-Coulomb model was used to model a slip-weakening fault slip behavior, enabling modeling of sudden slip that was interpreted as a seismic event, with a moment magnitude evaluated using formulas from seismology. In the case of CO_2 sequestration, injection rates corresponding to expected industrial scale CO_2 storage operations were used, raising the reservoir pressure until the fault was reactivated. For the assumed model settings, it took a few months of continuous injection to increase the reservoir pressure sufficiently to cause the fault to reactivate. In the case of shale-gas fracturing we considered that the injection fluid during one typical 3-hour fracturing stage was channelized into a fault along with the hydraulic fracturing process. Overall, the analysis shows that while the CO_2 geologic sequestration in deep sedimentary formations are capable of producing notable events (e.g. magnitude 3 or 4); the likelihood for such felt events is much smaller in the case of shale-gas fracturing. The reason is that CO_2 geological sequestration involves injection and pressure disturbances at much larger scale and with much larger reservoir permeability than in the case of shale gas fracturing. In the case of shale-gas fracturing, the expected low permeability of faults intersecting gas saturated shales is clearly a limiting factor for the possible rupture length and seismic magnitude. For a fault that is initially impermeable, the only possibility of larger fault slip events would be opening by hydraulic fracturing allowing pressure to permeate along the fault causing a reduction in the frictional strength over a sufficiently large fault surface patch and very brittle fault properties that would allow shear slip to develop over a sufficient large rupture area.

ARMA 15-0182

The influence of fracturing fluids on fracturing processes: a comparison between gas and water

Jiehao Wang[1,2], Derek Elsworth[2], Wancheng Zhu[3], Jishan Liu[4], Yu Wu[1]
[1]State Key Laboratory of Geomechanics and Deep Underground Engineering, China University of Mining and Technology, [2]Energy and Mineral Engineering, G3 center and EMS Energy Institute, The Pennsylvania State University, University Park, [3]Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, Northeastern University, [4]School of Mechanical and Chemical Engineering, University of Western Australia

Conventional water-based fracturing treatments may not work well for many shale gas reservoirs. This is due to the fact that shale gas formations are much more sensitive to water because of the significant capillary effect and the potentially high contents of swelling clay, each of which may result in the impairment of productivity. As an alternative to water-based fluids, gaseous stimulants not only avoid this potential impairment in productivity, but also conserve water as a resource and may sequester greenhouse gases underground. During the gas fracturing processes, gas will penetrate into the borehole wall due to the low surface tension and low dynamic viscosity of the fluid and the evolution of the fractures results from the coupled phenomena of gas flow, solid deformation and damage. To represent this, a coupled model of rock damage mechanics and gas flow is presented.

We investigate the fracturing processes driven by pressurization of gas within a borehole and compare it with water-based fracturing. Simulation results indicate that gas fracturing indeed has a lower breakdown pressure, as observed in experiments, and may develop fractures with greater complexity than those developed with water-based fracturing. We explore the relation between the fracture initiation pressure, breakdown pressure and complexity of fractures to both the interfacial tension and the dynamic viscosity of the fracturing fluids. It is shown that the fracture initiation pressure and breakdown pressure increase and the complexity of the resulting fracture networks decreases with increasing interfacial tension and dynamic viscosity. These conclusions are consistent with experimental observations.

ARMA 15-0570

Numerical Model of Hydraulic Fracturing Fluid Transport in the Subsurface with Pressure Transient and Density Effects

Daniel Birdsell[1], Harihar Rajaram[1], Hari Viswanthan[2], David Dempsey[2,3]
[1]University of Colorado at Boulder, [2]Los Alamos National Laboratory, [3]Stanford University

Understanding the transport of hydraulic fracturing (HF) fluid that is injected into the deep subsurface for shale gas extraction is important to ensure that shallow drinking water aquifers are not contaminated from an environmental and public health perspective and to understand formation damage from an oil and gas production perspective. Upward pressure gradients, permeable pathways such as faults or improperly abandoned wellbores, and the density contrast of the HF fluid to the surrounding brine encourage upward HF fluid migration. In contrast, the very low shale permeability and the imbibition of water into partially-saturated shale may sequester much of the HF fluid. Using the Finite Element Heat and Mass Transfer Code (FEHM), single-phase flow and transport simulations are performed to quantify how much HF fluid is removed via the wellbore as flowback and produced water and how much reaches overlying aquifers; imbibition is calculated with a semi-analytical one-dimensional solution and treated as a sink term. The amount of HF fluid that reaches the shallow aquifers is highly dependent on the amount of water imbibed and the suction applied to the well. In the presence of a permeable pathway that connects the hydrocarbon-rich shale to the overlying drinking water aquifer, the pressure transient due to injection and the density contrast allows rapid upward plume migration at early times. The density contrast diminishes considerably within tens of years as mixing occurs. We present estimates of HF fluid migration to shallow aquifers during the first 1,000 years after hydraulic fracturing begins for ranges of subsurface properties. Unlike most previous modeling studies, our study accounts for the combined effects of buoyancy, pressure transients in the wellbore, and imbibition.

ARMA 15-0075

A Numerical Study of the Parameters that Affect the Induced Principal Stresses by Hydraulic Fracturing in a Shale Formation

Yasser Akbarzadeh[1], Hugh Miller[2]
[1]Colorado school of Mines, [2]Colorado School of Mines

Hydraulic fracturing is a common method that has been used in mining, petroleum and geotechnical engineering for several years. It is a process of initiating and propagating fracture in the subsurface rock by utilizing a pressurized fluid . Understanding the effects of in-situ stress, internal injection pressure, and borehole radius on the induced principal stresses is critical in any hydraulic fracturing design.

A finite difference method (Itasca Flac2D) has been applied to study a horizontal borehole developed through a shale formation during hydraulic fracturing. The structural impact of differential internal fluid pressures on the borehole periphery has been studied utilizing the numerical method. The research is focused on the effect of critical parameters associated with the hydraulic fracturing on the largest principal stress and differential principal stresses in the rock. According to Coulomb's criterion, failure occurs when the maximum principal stress reaches the ultimate strength of the material for simple tension. Based on this theory, the largest principal stress will initiate cracks in the rock and lead to the failure of rock mass. The goal was to observe the effect

of borehole radius, internal injection pressure, and K (horizontal stress/vertical stress), on the induced maximum principal stress and differential principal stress. Largest principal stress is considered one of the key factors to initiate fractures in the rock. It was observed that increasing internal pressure, borehole radius, and K will significantly increase the induced maximum principal stress and differential principal stresses around the borehole.

ARMA 15-0713

Development of a geoperidynamic model for hydraulic fracture

John Edmiston[1]

[1]*Lawrence Berkeley National Laboratory*

The numerical simulation of fracture initiation and propagation in porous solids is a difficult problem due to the demanding combination of requirements, such as the ability to evolve arbitrary three-dimensional fracture surfaces along with an ability to reproduce the standard poroelastic response. Peridynamics has been successful in simulating dynamic impact and fragmentation problems as well as in delamination of composite materials. However details of its application to porous solids have not previously been reported. In this talk we describe the development of an ordinary state-based peridynamics theory for geomechanics (geoperidynamics). We verify our formulation using standard test poroelastic test problems such as Terzaghi consolidation. Finally we give early findings from applying the method to hydraulic fracture simulation.

Technical Session 7 – Elizabethan AB
Rock Mass Behaviors and Characterization

Monday, June 29, 2015, 11:00 am - 12:30 pm

Chairs: John Kemeny & Lianyang Zhang

ARMA 15-0044

Weathering Profiles of Some Sandstones from Sunshine Coast, Australia - Morphological and Geotechnical Approach

EDUARDO MARQUES[1], DAVID WILLIAMS[2]

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This paper presents the results of a study of the morphology of weathering profiles of some sandstones located in Sunshine Coast, Southeast Queensland, Australia. Several cut slopes were analyzed in order to provide accurate knowledge of their morphological characteristics. From these, five outcrops were selected to a more detailed description of their physical, geological, structural and geotechnical parameters, focusing on weathered rock materials including several characteristics of the rock matrix (fabric, mineralogy, degree of weathering, etc.) and rock mass (rock:soil ratio, discontinuity characteristics, JRC, JCS etc.). Samples from the upper portion of the profiles, into the transition zone between rock and soil, were collected in order to determine physical indices, preparation and description of thin sections, description of macroscopic characteristics and point load tests. The results show that sandstones weathering profiles are relatively thin and the contacts between different material layers are sharp. A strong structural conditioning of weathering can be noted in all outcrops. Soil like material is present only in portions of the rock mass close to the ground surface or along some sedimentary discontinuities (bedding). A remarkable characteristic of the studied weathering profiles is the presence of stress relief joints parallel to bedding, which plays an important role in the differentiation of the rock mass layers and weathering. Physical parameters, especially apparent porosity and density, have proved to be good indicators of weathering of rock matrix weathering. Microscopic indexes have also shown continuously variation along weathering profiles grades. For the rock mass, the best parameters to be used for the individualization of weathering grades is soil:rock ratio and fracturing index.

ARMA 15-0613

Numerical Simulation for Shear Behaviors of Rock Joints under Direct Shear Test

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This paper employs Particle Flow Code in 2 dimension (PFC^{2D}) to simulate shear behaviors of rock joints under direct shear tests. A series of rock joints, regular joints with different roughness angles and irregular joints with variable JRC (Barton suggested profiles) are investigated. Shear resistance-shear displacement relation, shear strength parameters, crack propagation (Fig. 1), and failure modes are observed and investigated. Based on the numerical simulation result, regular joint models, the simulation results compared well with Patton (1966) and Chang (1988) shear strength models in higher and lower normal stresses, but only compared well with Chang (1988) in critical normal stresses (Fig. 2). For irregular joint models, simulation results compared well with Barton (1977) estimation in low normal stresses (< 3MPa). In higher normal stresses (≧3MPa), Barton (1977) will overestimate this paper simulations. Three failure modes (Chang, 1988) were observed in this paper, (1) Mode I, failure occurs in lower normal stress; (2) Mode III, failure occurs in critical normal stress; (3) Mode IV, failure occurs in higher normal stress (Fig. 3). Scale effects were not be observed in this paper, as same as Ueng et al. (2010) and Zou (2002) experimental tests.

KEYWORDS: numerical simulation, PFC^{2D}, rock joint, direct shear test, failure mode.

ARMA 15-0236

A CREEP CONSTITUTIVE MODEL CONSIDERING GEOMETRIC DAMAGE OF FRACTURED ROCK MASS AND ITS APPLICATION

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More and more large-scale underground power houses are under complex geological environment of great buried depth and high in-situ stress. Meanwhile, it is complicated to analyze the long-term stability of underground caverns owing to the existence of joints in the surrounding rock mass. The joints make the degradation effect of the surrounding rock mass. According to these features, a new visco-elasto-plastic constitutive model is proposed. The model has a comprehensive consideration of geometric damage of the fractured rock mass. Besides, regarding VC++ as a terrace , we use the secondary development function of FLAC3D to make a program of this constitutive model. It is a Dynamic Link Library (DLL) and it can be used by the main program of FLAC3D. The new damage creep model of fractured rock mass is developed. In the project of Shuangjiangkou underground power houses in Sichuan, China, we use this program to analyze the long-term stability of underground caverns and guide the design of engineering. The results show that: it is quite strong feasible to use this new damage creep model to simulate the excavation of large underground caverns and analyze the long-term stability, and the analysis results can be used to guide the construction of engineering.

KEYWORDS

Damage creep model; fractured rock mass; underground caverns; numerical simulation

ARMA 15-0503

Use of Rock Mass Classification in prefeasibility studies: An illustrative study

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Rock mass classification (RMC) plays a pivotal role in the design of excavations in both civil and mining engineering. It is a quick and an uncomplicated powerful tool to assess stability of excavations as well as the support requirements of the same. Rock mass deformation properties can

also be determined using RMC systems. While it is so easy to use them, one needs to have the requisite technical skills to comprehend the theory underlying each classification system together with its limitations. This approach in using rock mass classification systems minimise abuse and ensures maximum benefit from them. The author also briefly discussed some of the ways to address serious concerns about RMC systems.
This paper is based on a prefeasibility project requiring initial estimates of support needed to stabilise excavations made in a rock mass. It features the assessment of stability and support requirements of a combination of a metro tunnel, metro station and ventilation raisebore excavations. Bieniawski's Rock Mass Excavability index (RME) was utilised to determine the advance rate expected for the raisebored tunnel.
Prior to giving the technical solution of the project question, a critical review of relevant papers which contribute knowledge to solving the problem was carried out. This facilitates the reader to easily follow the discussions and arguments presented in this paper. The paper presents a typical scoping study engineering report which sought for the necessary information on which a reliable decision on whether to proceed with the project or not could be made. A brief review of other classification methods was done in line with the research need. The author arrives at a decision that the project can be proceeded with as long the support recommendations are adhered to. The cost of the project can be recovered from the business of transporting passengers and materials through the tunnel, which can be convenient and time saving.

ARMA 15-0493

Investigation of Roughness Algorithms Applied to Joint Roughness Coefficient Profiles for Assessment of Weathering

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The roughness and associated shear strength of discontinuities has long been an important aspect of rock engineering. An early experimental study by Patton (1966) related normal force and roughness to shear behavior. All students, practitioners, and researchers in the field of rock mechanics are familiar with the joint roughness coefficient profiles developed by Barton and Choubey (1977). This seminal tool has been instrumental in the development of roughness and shear strength assessment of discontinuities.

The joint roughness coefficient profiles has also served as an inspiration to researchers attempting to assess the weathering state of rock. It has been well documented that weathering increases roughness. Unfortunately roughness is an arbitrary measure; it is scale dependent and for its use in quantifying weathering, there is no single satisfactory scale (Gomez-Pujol et al., 2006).

This study presents the results of exploring eight different roughness algorithms using the joint roughness coefficient profiles and coefficients presented in Barton and Choubey (1977). The roughness algorithms incorporated in this study are Z2, International Roughness Index, mean absolute distance, sinuosity, standard deviation, average semivariance, fractal dimension, and power spectral density. These algorithms have been used in various fields of study including rock mechanics, geomorphology, pavement engineering, and electrical engineering. The joint roughness coefficient profiles were scanned, read into MATLAB®, and digitized to provide a single trace at pixel resolution. The eight algorithms were applied to the traces at the original resolution and at two downsampled resolutions to assess how sampling scale impacts correlation with joint roughness coefficient values. Applying the algorithms yielded eight different roughness indices.

Comparison of the roughness indices with the JRC values yields one of two general shapes; either a generally (but sometimes monotonically increasing) curve with occasional small peaks at JRC 6-8 and JRC 12-14 or a bimodal shape that peaks consistently at JRC 10-12 and JRC 14-16 followed by a sudden drop in roughness. The standard deviation demonstrates remarkable consistency between sampling intervals but the shape of its curve also suggests that it is insufficient in quantifying JRC roughness alone. The final portion of the study, which is not yet complete, will present examples of surface scans of weathered limestone specimens and the associated roughness indices.

ARMA 15-0614

Variability of mechanical properties of bimrock

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Variability of mechanical properties of bimrock

Abstract
This paper used PFC^{2D} to simulate bimrocks mechanical behaviors under uniaxial compressive tests, and presents the means and variances of uniaxial strengths, Young's modulus, and poisson's ratios, respectively, for various volume fractions (V_f = block volume/total volume) and strain gauge lengths. The results show that uniaxial compressive strength (UCS), Young's modulus (E_{50}), and poisson's ratio (v) will increase when V_f increases, where simulated Young's modulus and poisson's ratio were compared well with differential scheme (DS) and Hashin and Shtrikman bounds (HS bounds) (Fig. 1). For quantifying the uncertainty of Young's modulus and poisson's ratio measurements by using strain gauge, the measurement uncertainties will increase firstly then decrease with increasing V_f (Fig. 2); when V_f =0.3~0.4, there has a maximum value, and minimum value is at V_f =0 or 1. In addition, crack propagation was also observed in this paper; when stress state at 80%~90% UCS before peak, few micro cracks were randomly dispersed in models. After peak stress, these micro cracks will rapidly propagate to macro fractures (Fig. 3). Furthermore, three different bonded materials (matrix-matrix bonds, block-block bonds, and block-matrix bonds) were monitored during the tests, to understand the failure mechanism of bimrock.

KEYWORDS: numerical simulation, PFC^{2D}, bimrock, uniaxial compressive test, uncertainty, crack propagation

Technical Session 8 – Elizabethan CD
Cave Mining Geomechanics

Monday, June 29, 2015, 11:00 am - 12:30 pm

Chairs: Fidelis Suorineni & John Henning

ARMA 15-0009

Use of digital imaging processing techniques to characterise block caving secondary fragmentation and implications on a proposed Cave-to-Mill approach

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Ore fragmentation in a block caving process occurs in three separate stages: in-situ fragmentation, primary fragmentation and secondary fragmentation. In-situ fragmentation is the original condition of rock fragmentation before an undercut is blasted. Loading conditions imposed on the rock mass by the caving process leads to primary fragmentation, as a combination of failure along existing discontinuities and fracturing of the intact rock. Secondary fragmentation is the reduction in size of primary fragmentation blocks as they move down through the ore column to the drawpoints. Secondary fragmentation has long been discussed as a key parameter of evaluating block caving productivity, such as to assess the possibility of hang-ups, which is caused by the large boulders stuck in a drawbell due to poor fragmentation. Overall, the fragmentation produced during the caving process controls the overall success and profitability of a block caving operation. However, fragmentation is extremely difficult to measure in a reliable and routine manner. For example, in-situ fragmentation could be estimated based on a characterization of the natural fracture network, while secondary fragmentation could be measured by means of physical methods and image processing techniques.

Within this context, this paper focuses on the use of digital imaging processing techniques to obtain the overall size distribution of rock blocks at the drawpoints. A photogrammetric analysis code (Wipfrag) and a 3D imaging tablet (PortaMetrics) were used to characterise secondary size distributions for an operational cave mine at various stages of mining.
To the authors' knowledge, no significant research has been carried out to date relating caved ore size and hardness on mill performance, also referred to as a Mine-to-Mill approach. It is anticipated that the results of this work will feed into a larger initiative at the University of British Columbia pursuing research on Cave-to-Mill, a proposed new approach to integrate cave mining with milling processes to improve production and forecasting capabilities. The variable and relatively uncontrollable nature of cave fragmentation is considered to be a key distinguishing feature of the suggested Cave-to-Mill approach when compared with typical Mine-to-Mill strategies for open-pit mines.

ARMA 15-0010

A joint asperity degradation model based on the wear process

Yingchun LI[1], Joung OH[1], Rudrajit MITRA[1], Bruce HEBBLEWHITE[1]
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Joints can significantly affect the mechanical behaviour of rock masses. The presence of a joint set is crucial to the initiation and propagation of caving. A numerical approach to cave assessment requires a realistic joint constitutive model, and therefore produces better prediction of the cavability of the orebody. An asperity degradation model for rock joints has been developed that considers the progressive abrasion of a true roughness area over joint sliding. The magnitude of dilatancy is predicted to be decreased exponentially with the increase in shear displacements. The degradation in dilation and post-peak strength along asperities is modelled on the basis of the wear process. Then, geometric conditions and rock strength are considered through the dimensional analysis. Experimental studies of direct shear tests have been conducted using triangular-shaped asperities and the results are correlated with the model's behaviour to demonstrate its performance. The proposed joint model can be readily implemented in numerical procedures such as discrete element method and used to simulate block or panel caving.

ARMA 15-0257

Case Study: Understanding the mechanics behind the rockmass deformation observed in an extraction drive at New Gold's New Afton Mine block cave operation

Andy Davies[1]
[1] *NewGold Inc, Canada*

The New Gold New Afton Mine is a 5 million tonne per year operating block cave mine located 8km outside of Kamloops, British Columbia, Canada. The current extraction level is at 615m below surface and the current mining footprint is approximately 800m in length by 120m in width. At its current size, New Afton is one of the smallest producing block caving operations in the world. The ore being mined is a copper-gold porphyry deposit situated within the Iron Mask batholith complex, is bounded by 2 major fault structures and dips near vertically to the south-southeast and plunges southwest. The bulk of the economically viable portion of the deposit is highly jointed and rockmass quality is in the order of 35 - 45 ($RMR_{76,\ *\ \mathrm{Bieniawski}}$), placing it in a poor to fair classification category.
The case study presented here focusses on a single strike drive located on the southern abutment of the cave. An excavation that has been subjected to numerous rehabilitation operations and campaigns since caving started early in 2012. In an attempt to provide support solutions and longevity to this vital production drive, several analyses were carried out using data obtained from instrumentation, numerical modelling, laboratory testing of samples, geotechnical mapping and regular field observations of support performance and modes of deformation.
Notably, the results and learnings from the analyses conducted on this drive have provided us with essential knowledge on how to be pro-active in dealing with future drives that may be subjected to similar rockmass deformation.

ARMA 15-0571

The Use of Numerical Methods in Simulating the Influence of Geological Structure on the Surface Subsidence Associated with Sub-Level Caving

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[1]Simon Fraser University, [2]University of British Columbia, [3]LKAB Kiruna Mine

Sub-level caving is a cost-efficient mining method that allows for a high degree of mechanization and automation. Ore extraction using this technique leads to the formation of significant surface subsidence in the hangingwall. Large scale geological structures such as faults may play a very important role in subsidence development. Sub-level caving involves both large displacements and rock fragmentation therefore, an appropriate modelling approach must allow simulation of these two main components. The hybrid finite/discrete element method allows a realistic modelling of fracturing through simulation of the transition from a continuum to a discontinuum state. An integrated finite/discrete element method-discrete fracture network (FDEM-DEM) modeling approach is employed in this paper to investigate the influence of jointing and faults on hangingwall surface subsidence in sub-level caving. A series of conceptual models are developed to investigate the influence of fault orientation and location on the hangingwall surface subsidence. The numerical results illustrate that the extent of surface subsidence is highly influenced by the mechanical and geometrical characteristics of major structures. New methods of characterising numerical displacements with time step are shown to provide additional insight into both sub-level caving failure mechanisms and associated subsidence.

Keywords: Sub-level caving, finite/discrete element method, discrete fracture networks, major geological structures, subsidence

ARMA 15-0638

INVESTIGATING BLOCK CAVING GEOMECHANICS USING SEISMIC SPACE-TIME SEQUENCES AND VIRTUAL REALITY SCIENTIFIC VISUALIZATION

James Tibbett[1], Fidelis Suorineni[1], Bruce Hebblewhite[1]
[1]The University of New South Wales, Australia

Block caving is an underground mining method that enables profitable extraction of massive, low-grade orebodies. The use of the block cave mining method is increasing in popularity due to the greater depth of deposits, depleted high-grade orebodies, and declining metal market prices. Despite the increasing trend towards block cave mining, the method still faces several challenges. Lack of access to the cave remains a major issue in understanding the rockmass response to mining for method optimisation. Improving the understanding of how a rockmass responds to caving will lead to safer, more predictable and more productive mining operations. Combining large datasets from multiple sources with virtual reality scientific visualisation (VRSV) is a viable alternative to understanding complex cave behaviour without access to the cave. This is achieved using immersive environments with the ability to view complex multi-dimensional data (beyond 3D) graphically. VRSV offers a unique platform where it becomes possible to immerse a multi-disciplinary team of experts, and/or a management team, in a virtual mine environment for quick decision making and fast resolution of conflicting conclusions. The underground mining system is complex due to multiple interrelating factors such as geology, excavation geometries, stress and time. Block caving is more complex than most underground mining methods due to the large scale of the operation, complex network of excavations and the reliance of natural factors in the fragmentation process. Due to this complexity, it is vital that the mining system is analysed holistically, rather than optimizing individual factors one at a time.

This paper describes the use of a customised software module developed for use in the Advanced Visualisation Interactive Environment (AVIE) at The University of New South Wales (UNSW), Australia, to enable VRSV investigation into block cave mining systems (BCMS). This work focuses on the detection and visualisation of seismic space-time clusters to further our understanding of caving geomechanics in the cave propagation phase. The combination of the VRSV tool and the seismic space-time cluster analysis has the potential to provide a near-real-time insight into the

dominant caving mechanisms in different regions across a mine. Insight into the rockmass response is gained through stereonet analysis of the cluster orientations and through analysis of the chronological evolution of these seismic space-time clusters. This work back analyses the cave propagation phase of a case study block caving operation with the view to further our understanding of cave propagation geomechanics.

KEYWORDS

Block caving, virtual reality, scientific visualisation, seismicity, seismic space-time clusters, large multiple source data, multi-dimensional data

ARMA 15-0842

Modeling Interaction between Natural Fractures and Hydraulic Fractures in Block Cave Mining

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Hydraulic fracturing has been utilized as a pre-conditioning method in block cave mining to improve cavability and fragmentation size in recent years. A successful hydraulic fracturing operation depends largely on the interaction between natural fractures and hydraulic fractures. This process has been extensively studied in the oil & gas industry where hydraulic fractures are commonly vertical planar types. In this case, the effect of natural fracture dip angle and vertical principle stress is neglected. However, in block cave mining, hydraulic fractures are generally horizontal radial types. The applicability of the existing conclusions for block cave mining needs to be examined. In this paper, the interaction between natural fractures and horizontal radial hydraulic fractures is investigated by theoretical analysis and numerical modeling. It indicates that both natural fracture dip angle and approach angle make influence on interaction result, as well as all the three principle stresses. It shows that hydraulic fractures are more likely to cross natural fractures if rock tensile strength is sufficiently low, or the product of flow rate and fluid viscosity is sufficiently high. Rock masses in block cave mining have mixed-qualities. High flow rate and fluid viscosity are recommended in regions where hydraulic fractures are not able to cross natural fractures.

Technical Session 9 – California West Geomechanics for Unconventionals

Monday, June 29, 2015, 02:00 pm - 03:30 pm

Chairs: Sandeep Mahajan & Marisela Sanchez-Nagel

ARMA 15-0437

Stress-dependent permeability model of laminated gas shale

Mikhail Geilikman[1], Sau-Wai Wong[1], John Karanikas[1]

[1]Shell International E & P

Because gas shales consist of organic and inorganic solid components, the stress and pore pressure dependence of permeability of shale gas rock is considered in the model of porous medium with two solid constituents recognizing that kerogen rich shale rock is at least a two-solid constituent porous rock, which broadly consists of organic (kerogen) and inorganic matter with significantly different mechanical properties. We consider lamellar morphology of organic and inorganic constituents. It is shown that the total mean stress in each of the constituents is different from the external confining stress even for homogeneous state of rock. For unconventional rock types such as gas shale, the question arises as to what exactly is effective stress. This leads to a more complicated dependence of permeability rather than that of Terzaghi effective stress, i.e. confining stress minus pore pressure as in the case of one-solid constituent porous medium. The provides a better description of effective stress, and better explain the dynamic impact of geomechanical stresses on key production parameters such as porosity and permeability. The model allows computation of effective Biot's pore

pressure coefficient and other effective stress coefficients starting out from those for each of solid constituents. Comparison of this model with classical theories and limited experimental work is performed. This new model is a generalization of the earlier developed spherical composite model [1] for more realistic laminated texture of gas shale rock. Additional dependence of permeability on pore pressure is captured by taking into account Knudsen and slip flow contributions. Because depletion-induced variation of pore pressure leads to variation of eigen-strain, the resultant strain and stress exerted at the reservoir by surrounding country rock is found by using Eshelby-type inclusion model. The depletion-induced evolution of reservoir permeability is expressed as a function of pore pressure. The model provides recommendation for maximum drawdown which still allows preventing collapse of porosity and permeability of softer organic constituent.

Geilikman, M. B., J. M. Karanikas, S.W. Wong (2013). “Permeability model of shale gas rock with variable solid mass”, Paper 349 presented at the 47th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA.

ARMA 15-0484

Relating Static and Dynamic Mechanical Anisotropies of Shale

Rune M Holt[1], Andreas Bauer[2], Erling Fjær[2], Jørn F Stenebråten[2], Dawid Szewczyk[1], Per Horsrud[3]

[1]NTNU, [2]SINTEF Petroleum Research, [3]Statoil

Anisotropy has become state-of-the-art in geophysics, but is most often neglected in geomechanical applications to petroleum engineering. Nevertheless, the laminated texture of shales leads to pronounced anisotropy, which has significant impact on e.g. hydraulic fracture growth, borehole failure and possibly also on *in situ* stresses.

We present laboratory data from undrained triaxial and unconfined tests, where all five elastic coefficients of (assumed Transversely Isotropic; TI) shale cores have been obtained using multi-directional P- and S-wave velocity measurements. These measurements permit computation of the angular dependence of Young's modulus and the Poisson ratios. Comparing with static moduli measured during the same tests on cores with different orientations, one observes that the dynamic moduli strongly exceed their static counterparts [1, 2]. The difference is larger during initial loading than during repeated load cycles. The angular dependence of static and dynamic moduli appears however to be similar, in particular for the moduli measured during unloading and reloading. An example, using data for Mancos Shale, is shown in Figure 1.

Measurements of Young's moduli and Poisson's ratios for samples with their axis normal to the bedding plane (E_V and ν_{VH}) and for samples with their axis in the bedding plane (E_H and ν_{HV}, the latter measured from radial strain normal to bedding) demonstrate within experimental uncertainty that

$$\frac{E_V}{E_H} = \frac{\nu_{VH}}{\nu_{HV}}$$

This verifies that TI symmetry is appropriate for the description of the shales that were studied.

Two mechanisms are identified as responsible for the observed static vs. dynamic discrepancy: Frequency dependence (dispersion) and finite strain effects (plasticity). Separate measurements of elastic moduli at low (1-100 Hz) frequency with less than 1 μStrain amplitude confirm the magnitude of dispersion as well as its anisotropy. Dispersion is further revealed through extrapolation of statically measured moduli to the state of elasticity existing at stress reversal [3]. Possible dispersion mechanisms will be discussed with basis in the experimental observations.

In order to fully convert dynamic to static data, the effect of finite strain in the measurement of static moduli has to be understood. This is addressed by studying the evolution of plasticity during initial loading, and in particular looking into possible changes in static anisotropy between initial loading and unloading-reloading cycles.

ARMA 15-0768

Permeability Variations Associated with Various Stress State during Pore Pressure Injection

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The Steam-assisted Gravity Drainage (SAGD) process dominates the in situ recovery of oil sands and bitumen in Alberta, Canada. This process can be achieved only after the thermal and hydraulic communication between the injection well and the production well is established during the start-up operation. The conventional steam circulation start-up operation takes up to a few months to achieve the communication. An enhanced SAGD start-up operation strategy is desired and on demand for SAGD operation to shorten the time period. It is expected that the ability to create a dilation zone vertically connecting the two horizontal wells will increase porosity, permeability, and water mobility in the interwell region.

Lab scale experimentation is geomechanically engineered and carried out to evaluate permeability variations and volumetric strains during pore pressure injection. Reliable representative wet/oil sands specimens are required, through which to study the multiple phase flow behaviors and geomechanical responses in a triaxial test. Considering the difficulties of obtaining a non-disturbed representative field specimen, preparation of artificial oil sands sample provides an option to obtain a desired characteristic. A wet/oil sands core is then tested in a triaxial cell housed in an environmental chamber to simulate reservoir conditions in terms of stress state, temperature, and pore pressure. The series of experiment are carried out in a triaxial cell under either isotropic or anisotropic stress state.

This paper presents an improved technique and method to prepare a reliable representative wet/oil sands specimen for laboratory analysis. This packing technique deeply densifies sands specimen with high quality, which allows possessing almost identical geophysical properties in terms of porosity, relatively density, and dry density. A series of synthetic wet/oil sands core specimen have been prepared with different fluid saturation. The tailing pond sands packed in these core specimens are well representative for McMurray formation oil sands. The preliminary results from experiments show that the permeability variations are well associated with a stress state. Under isotropic stress state, a wet/oil sands core sample display a temporary improvement on the effective permeability. However, it shows promising potentials to permanently enhance the effective permeability and the porosity in the dilated zone under deviatoric stress state.

The approach of sands packing greatly enhances capability for researchers to study fundamentals related to reservoir engineering and geomechanical engineering. The experiment delivers fundamental constitutive data linking the geomechanical behaviour of wet/oil sands to its hydraulic-mechanical behaviour under various stress states, which provide supports on development of numerical and then improve the industry's ability to capture complex behaviour in their reservoir geomechanical simulations.

ARMA 15-0376

Helium-Mass-Spectrometry-Permeameter for the measurement of permeability of low permeability rock with application to triaxial deformation conditions

Stephen Bauer[1], Moo Lee[1], W. Payton Gardner[1]
[1]Sandia National Laboratories

A helium leakage detection system was modified to measure gas permeability on extracted cores of nearly impermeable rock. Here we use a Helium - Mass - Spectrometry - Permeameter (HMSP) to conduct a constant pressure, steady state flow permeability test through a sample using helium gas. Under triaxial stress conditions, the HMSP can measure hydraulic permeability of rocks and geomaterials down to the nanodarcy scale (10^{-21} m^2). In this study, measurements of flow through six shale samples under hydrostatic conditions were in the range of 10^{-7} to 10^{-9} Darcy.

We extend this flow measurement technology by dynamically monitoring the release of helium from a helium saturated shale sample during a triaxial deformation experiment. The helium flow, initially extremely low, consistent with the low permeability of shale, is observed to increase in advance of dilatant behavior (in this paper we use the term dilatancy to define the deformation stage in which volumetric compaction abruptly switches to volumetric increase during deformation) of the shale. This is perhaps the result of microfracture development and flow path linkage through the microfractures within the shale. Once dilatancy initiates, there is a 1 order of magnitude increase in helium release and flow. This flow rate increase is likely the result of development of a macrofracture in the sample, a flow conduit, later confirmed by CT post-test observations of the deformed sample. The release rate (flow) peaks and then diminishes slightly during subsequent deformation, however the post deformation flow rate is considerably greater than that of undeformed shale.

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ARMA 15-0189

Analysis of stress variations with depth in the Permian Basin Spraberry/Dean/Wolfcamp Shale

Shaochuan Xu[1], Mark Zoback[1]

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This research examines stress variation with depth in Midland Basin Spraberry/Dean/Wolfcamp Shale to understand the controls on vertical hydraulic fractures propagation. An interesting phenomenon of drilling-induced tensile fractures is observed in the image log. That is, there are drilling-induced tensile fractures in the Spraberry and Dean formation, but there are no drilling-induced tensile fractures in the Wolfcamp formation. This brings out a question: how variable is the stress state with depth? We estimate the pore pressure and the three principal stresses with depth to answer this question. The pore pressures in the study area are analyzed from the DFIT (Diagnostic Fracture Injection Test), which are consistent with the pore pressures documented in the literature. S_v is calculated from the density log. S_{hmin} in the Wolfcamp formation is picked up from the DFIT, while S_{hmin} in the Spraberry formation is obtained from literatures. S_{Hmax} in the Spraberry formation is constrained by using knowledge of P_p, S_{hmin}, and drilling-induced tensile fractures, but S_{Hmax} in the Wolfcamp formation is more difficult to obtain, because there are no drilling-induced tensile fractures or breakouts. Therefore, we constrain it through the estimation of UCS (Uniaxial Compressive Strength). Finally, the stress state with depth is obtained by plotting P_p, S_v, S_{hmin}, and S_{Hmax} with depth together. We find that the faulting regime is strike-slip/normal in the Spraberry formation, but changes into normal in the Wolfcamp formation. That is, the three principal stresses in the Wolfcamp formation are more isotropic than those in the Spraberry formation. Futhermore, We find the pore pressure variation is the dominant reason of absence of drilling induced tensile fractures in the Wolfcamp formation. The pore pressure gradients in the Spraberry formation are higher than the hydrostatic pressure gradients, while the pore pressure gradients in the Wolfcamp formation are lower than the hydrostatic pressure gradients. So the difference between the mud pressure gradient and the pore pressure gradient is the key factor to determine whether the drilling-induced tensile fractures appear or not. This work is important in two aspects: (1) we find the reason for upward propagation of hydraulic fractures is that the overlying Spraberry formation is under-pressured; (2) the fact that the stress is more isotropic in the Wolfcamp formation inspires us to build a creep model to study the stress relaxation.

ARMA 15-0351

Pore Pressure estimation in a Tight Sand Reservoir: Neuquén Basin, Case Study

Juan Pablo Alvarez[1], Marcos Mendoza A. [1], Emilio A. Winograd[1], Martin Sanchez[1]

[1] *Y-TEC*

Standard methods to predict pore pressure rely on the assumption that undercompaction is the only mechanism for overpressure generation. For conventional plays, this assumption may hold since the weight of the overlying sediments is supported partly by the rock matrix and partly by the confined interstitial fluids, resulting in an overpressured formation. In these cases, a thick mudrock layer usually acts as seal of thin sandstone reservoirs and the source rock is located at a certain distance of the reservoir.

The studied reservoir is located in the Neuquen basin in the west central Argentina. The formation is a thick succession (400 m) of very low permeability (<0.1mD) sandstones sequence, and is defined as a "Tight Gas Sand" unconventional reservoir. In this type of reservoirs, it becomes necessary to check the methodologies to predict pore pressure, since the source of overpressure is not clear and the absence of a thick mudrock layer does not allow to find trends of preserved porosity in fine layers.

This paper shows a workflow to generate a pore pressure model at reservoir scale in a Tight Gas Sand reservoir. Sonic log, density log and DFIT data of around 50 wells were used to correlate the porosity with the vertical effective stress (VES), which is the difference between the overburden and the pore pressure. This methodology allowed to obtain a robust empirical correlation between sonic logs and pore pressure, that was adjusted in the entire reservoir and took into account the mechanism of overpressure generation.

Technical Session 10 – California East

Thermal, Mechanical, Chemical and Biological Processes

Monday, June 29, 2015, 02:00 pm - 03:30 pm

Chairs: Mileva Radonjic & Adrienne Phillips

ARMA 15-0143

Experimental assessment of the influences of temperature on geomechanical characteristics of a carbonate reservoir

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Petroleum Geomechanics is a multidisciplinary branch of petroleum sciences which aims to diagnose, control and model the mechanical behavior of subsurface geo-materials including reservoir rocks and overburden or underburden formations. Main geomechanical properties are usually obtained from destructive tests (on core samples) using standardized laboratory procedures. Due to the practical investigations, the mechanical characteristic of reservoir rocks should be measured at the reservoir conditions (such as reservoir temperature and pressure). In this regard, in this study first 6 rock types of carbonate reservoir formation (one of Iranian hydrocarbon field) have been defined and 24 plugs (4 plugs from each rock type) taken from coring interval. Afterward uniaxial compression tests have been carried out in both ambient and reservoir (90° C) temperatures on core samples. Finally extracted geomechanical properties in both temperatures, including UCS (uniaxial compressive strength), E (Young's modulus), v (Poisson's ratio), were compared. The results illustrated that; temperature implementation in the uniaxial compression test process directly affects the ultimate strength of rock samples and different rock types show different kind of alteration (ultimate strength increases or decreases). In addition, Although Young's modulus values vary from one rock type to another, but temperature implementation on testing process has almost no effect on this parameter for each rock type. In other word Young's modulus values of each rock type are constant in both reservoir and ambient temperatures. Moreover experimental results showed that not only there is no significant difference among values of Poisson's ratio of each rock type, but also this parameter is not sensitive to temperature changes. The average value of Poisson's ratio is about 0.31 in both conditions.

ARMA 15-0490

Biological influences in the subsurface: A method to seal fractures and reduce permeability with microbially-induced calcite precipitation

Adrienne Phillips[1], Robin Gerlach[1], Randy Hiebert[2], Jim Kirksey[3], Lee Spangler[1], Richard Esposito[4], Al Cunningham[1]

[1]Montana State University, [2]Montana Emergent Technologies, [3]Schlumberger Carbon Services, [4]Southern Company

To manage the environmental risk profile of geologically-stored carbon dioxide or unconventional oil and gas resource development, methods are needed to prevent leakage of subsurface fluids to functional overlying drinking water aquifers or the ground surface. One method that has been explored on multiple scales (from laboratory to field) is the use of microbially-induced calcite precipitation (MICP). Microbes hold the capability to alter the chemical environments in host rock pore spaces. One example is the use of ureolytic microorganisms that contribute enzymes to create saturation conditions favorable for promoting MICP. MICP has been proposed for a number of subsurface engineering applications including preventing gas leakage by sealing fractures to secure geologic storage of CO_2 or other fluids, improving wellbore integrity, and stabilizing fractured and unstable porous media.

Traditionally, cement is used to repair well bore integrity issues and leakage pathways. Leakage pathways may develop during the well completion process (incomplete cement job) or may form post completion when the stresses of injection and extraction cause fractures or delaminations between the casing and cement or cement and formation. Some of the leakage pathways may not be large and thereby inaccessible to traditional cement squeeze repair methods. The use of a sealing technology involving microbes has an advantage that microorganisms are small, ~2μm. This suggests small aperture fracture sealing could be achieved. The promotion of MICP in the subsurface is a complex reactive transport problem coupling microbial, abiotic (geochemical), geomechanical and hydrodynamic processes.

In the laboratory, MICP has been demonstrated to cement together heavily fractured shale and sandstone cores and reduce permeability up to five orders of magnitude under both ambient and subsurface relevant pressure conditions (Figure 1). Most recently, a MICP fracture treatment field study was performed at a well at the Southern Company Gorgas Steam Generation Plant (Alabama) (Figure 1). The Fayetteville Sandstone at approximately 1120’ below ground surface was stimulated prior to MICP treatment. After 4 days of injection of 24 calcium pulses and 6 microbial inoculations, injectivity of brine into the formation was significantly reduced. The experiment also resulted in a reduction in pressure decay, a measure of improved wellbore integrity. These promising results suggest the potential for MICP treatment to seal fractured pathways at the field scale.

ARMA 15-0727

Fracture-aperture alteration induced by calcite precipitation

Trevor Jones[1], Russell Detwiler[1]

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Mineral precipitation significantly alters the transport properties of fractured rock. Chemical solubility gradients that favor precipitation induce mineral growth, which decreases the local aperture and alters macro-scale flow properties. Understanding the resulting development of spatial heterogeneities is necessary to predict the evolution of transport properties in the subsurface. We present experimental results that quantify the influence of aperture variability on the evolution of mineral growth patterns in a transparent, analog fracture. Prior to flow experiments, a pump circulated supersaturated calcite solution over a piece of flat glass, coating the surface with calcite. This method of seeding resulted in small clusters of calcite crystals that were distributed uniformly across the bottom fracture surface. The coated surface was mated with rough-walled glass to create a variable-aperture fracture with a mean aperture of 155 μm. A continuous flow ISCO pump injected a reactive fluid into the fracture at 0.5 ml/min. The fluid was a metastable mixture of sodium bicarbonate (NaHCO3, 0.02M) and calcium chloride (CaCl2, 0.0004M), with a saturation index, Ω, of 8.51 with respect to calcite. A strobed LED panel backlit the fracture and a high-resolution CCD camera monitored changes in transmitted light intensity. Light transmission techniques provided quantitative measurements of fracture aperture over the flow field. Our experiments demonstrate that when reactions are limited by kinetics, minerals will preferentially grow in small apertures near the inlet. This enhances preferential flow through high-transmissivity regions and has little effect on fracture-scale permeability. These results differ from mineral growth predictions in constant-aperture fractures that suggest a rapid decline in fracture-scale permeability, resulting from uniform precipitation across the fracture-width. Future experiments will quantitatively investigate growth patterns and permeability alterations in constant-aperture fractures.

ARMA 15-0498

Microstructure and Micromechanics of Wellbore Cements under Compression and Thermal Loading

Hui Du[1], Ruixuan Guo[1], Mileva Radonjic[1]
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The primary objective of wellbore cement is to provide zonal isolation as a hydraulic barrier. During the lifetime of a well, cement has to cope with variations in stresses and temperatures. Changing in stresses and temperatures can cause cement deformation, which may leads to damage of cement sheath integrity, resulting in loss of zonal isolation and sustained casing pressure. This study investigated the effect of the mechanical compression and cyclic temperature variations on the mechanical properties of the cement, such as hardness and Young's modulus; furthermore, the effect of cement designs was also studied including water to cement ratio (w/c), salinity and chemical additives.
Micro indentation tests were conducted on varies cement designs to evaluate the changes in mechanical properties under different circumstances. A Vickers diamond indenter tip was driven into the cement specimen, by applying an increasing normal load, and the position of the indenter relative to the sample surface was precisely monitored with an optical non-contact depth sensor. Analysis of indentation test results on the cement samples showed: (a) a decrease in hardness and Young's Modulus right after compression while an overall increase one month after compression; (b) cyclic temperature variations significantly decreased neat cement hardness and Young's Modulus, but this effect varied when cement had other chemical additives; (c) hardness and Young's Modulus decreased after increasing water to cement ratio and/or water salinity. This unique research provided an important insight to propose appropriate cement design to avoid cement failure and prolong cement sheath durability.

KEYWORDS
Micro indentation, Wellbore cement compression, Mechanical properties, Cement sheath integrity

ARMA 15-0539

Effect of Fracture Heterogeneities on Reactive Flow

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[1]Schlumberger-Doll Research

The interplay between chemical reactions and mechanical deformation governs permeability evolution in field operations involving reactive fluids, such as CO_2 and acids. While mechanical compression decreases the permeability of a fracture, fluid-rock reactions can increase it or decrease it by means of mineral dissolution or precipitation, respectively. In addition, the cumulative effect is strongly influenced by geological and operational characteristics such as temperature, pressure, rock mineralogy, fluid flow rate, fluid composition, and local boundary conditions (fixed-stress versus fixed displacement). In this paper, we present an experimentally calibrated modeling framework consisting of distinct reactive-flow and geomechanical modules. The reactive-flow module predicts aperture evolution due to fluid-rock reactions. The aperture evolution under a fixed displacement

boundary condition is fully described by the reactive-flow module. The geomechanical module predicts the change in aperture due to mechanical deformations of fracture surfaces and asperities required to balance the imposed stress. The aperture evolution under the fixed stress boundary condition is described by the coupled reactive-flow and geomechanical model. Our model confirms the relevance of coupling reactive flow with geomechanics for a fixed stress boundary condition. It also captures the sensitivity of the aperture evolution to the relative rates of advection, diffusion, and reaction. Here, we use synthetic aperture fields having a range of values for roughness and correlation length-scales to investigate the effect of geometrical heterogeneity on the evolution of fracture apertures. We also investigate the effect of mineralogical heterogeneity on the aperture field by using spatially dependent reaction rates. Finally, we present experimental results of reactive flow through fractured cores subject to mechanical stresses and compare effluent concentration, pressure drop, flow rate, and final aperture with the predicted results to evaluate the validity of the coupled model.

ARMA 15-0657

Impact of Compression on Petrophysical and Mechanical Properties of Wellbore Cement Containing Salt

Arome Oyibo[1], Mileva Radonjic[1]
[1]*Louisiana State University*

Salt is usually added to oil well cement systems to overcome compatibility issues between well cements and salt containing formations as well as salt related durability issues with cement sheath. Several studies on the impact of adding salt to oil well cement have been documented in the literature; however, the impact of compression on salt cement sheath such as during hydraulic fracturing has not been fully investigated. This study focuses on investigating the impact of compression (cement's compaction) on the petrophysical and mechanical properties of wellbore cement containing salt.
A unique bench-scale physical model which utilizes expandable tubulars was used to simulate the compaction of a previously cemented casing under field-like conditions. An expandable cone was used to expand the inner pipe of the pipe inside pipe composite assembly with a cemented annulus, and the pipe expansion in turn compresses the cement sheath behind it. The impact of the compression on the cement's petrophysical and mechanical properties were quantified by measuring the porosity, permeability and hardness of the 1 x 2-in salt cement cores drilled from the compacted cement sheath. The results obtained indicate that the compaction of the cement sheath resulted in a reduction of porosity and permeability of the cement sheath. Also, an increase in the hardness of the cement sheath after the compression was also observed and the detrimental effect of salt on the strength and stiffness of the cement were reduced by the compaction process.
SEM, EDS and MIP techniques were used in mineralogical, microstructural and pore quantification of the cement sheath after the compaction experiments respectively. The result highlights mineralogical changes within the cement as well as reduction in pore throat sizes of the salt cement matrix due to compression.
The findings from this study present a basis for a deeper understanding of the impact of compaction on oil well cements containing salt.

Technical Session 11 – Elizabethan AB
Tunnels and Caverns 1

Monday, June 29, 2015, 02:00 pm - 03:30 pm

Chairs: Joseph Wang & Hehua Zhu

ARMA 15-0480

Underground Research Laboratories for conducting fault activation experiments in shales

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Since a decade, observations and experiments conducted in underground environments worldwide (mines, underground research laboratories - URL) allowed to bridge the scale gap between laboratory scale and large scale faults. Underground rock laboratories allow developing decameter scale relatively well constrained experiments at the smallest distance from the hypocenters. URL experiments allowed developing new monitoring technologies coupling pressure-strain-seismic measurements and reproducing complete earthquakes sequence analogue to natural ones. They also allowed exploring past movements of faults, paleofluids in three dimensions, and characterizing different fault architectures and hydromechanical properties in unaltered conditions. This is particularly important for faults in clay formations which typically cannot be observed at the Earth's surface because of the high alteration. Here we show how examples from the Mont Terri (Switzerland) and Tournemire (France) URLs may help in (i) conceptualizing fault architectures in shales, and (ii) estimating fault hydromechanical properties from field decameter scale experiments. The concept is to pressurize the fault core using a straddle packer system across a fault. A three-dimensional displacement sensor in the pressurized interval, and a distributed deformation flute set in a monitoring hole one meter apart from the injection hole allowed continuous synchronous coupled monitoring of fault movements, injection pressure and flow rate.

Some key results are that shale faults that are critically stressed or at the rupture limit can be reactivated due to moderate stress variations comparable to stress variations associated with shallow underground excavations. Furthermore, micrometer-to-millimeter scale reactivations may lead to large factor-of-10-to-more increase in permeability without generating significant seismicity. This appears to be more related to complex multi-scale geological processes linked to fault history such as differential hardening, partial sealing, pressure solution and gouge development within the fault zones than to the regional state of stresses. These unique results are of great importance in evaluating fault seal integrity in oil and gas exploration, production or CO2 storage, and underground excavations in close vicinity to fault zones.

ARMA 15-0176

Induced Rockbursts and Inherent Rockbursts

Jian Deng[1]

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Rockbursts are sudden and violent failure of rocks in deep and/or high stress tunnels or underground mines. They are responsible for high fatality rates, losses in production and equipment, and a detrimental influence on the recruitment of labor. Researchers have proposed an analogy between the violent failure of a rock sample on a testing machine and the dynamic rock fracture during rockbursts in engineering practice (Cook, 1965, 1967; Gill et al., 1993; He et al., 2010). Cook (1967) discussed the post-peak behaviour of a body of rock specimen in relation to rockbursts. However, in engineering practice even in deep mining, the in-situ or the secondary stress rarely reaches the peak value of rock strength, not to say the post peak phase. The occurrence of rockbursts

is not necessarily always located at the point of the highest stress. In this sense, inherent rockbursts are different from strain rockbursts. Another serious problem of using rock specimen to study rockbursts is that it does not consider the influence of geo-structures on rockbursts, which directly leads to the drawback that it does not differentiate the pillar rockburst, roof rockburst, or tunnel rockburst. The dynamic failure characteristics of materials and structures are quite different (Shukla et al, 2010).

It has been found that some rockbursts are induced by dynamic fluctuation from mining excavations or other sources of vibrations, such as drilling or blasting in adjacent stopes, but some rockbursts occur without any stimulation outside. The paper attempts to investigate the inherent and induced mechanism of pillar rockbursts in hard rock mines. By considering rockburst as an instability problem of structures, rockbursts are classified into inherent rockbursts and induced rockbursts according to their occurrence without or with stimulation forces. Inherent rockbursts occur only when a mining structure becomes unstable under static loadings, whereas induced rockbursts happen where the causative factor is dynamic loadings. Rigorous mathematical models are set up for fontal rockbursts and induced rockbursts respectively. The conditions of rockburst occurrence of a pillar are obtained by solving the problems of static instability or dynamic instability (Figure 1). For inherent rockbursts, the quatitative relation between the loads/stresses and rockbursts is derived. For induced rockbursts, the quantitative relation between blasting and induced rockbursts is established and parametric resonance mechanism of induced pillar rockbursts is discovered. Contrary to conventional methods where only rock materials or rock specimen were used to study rockbursts, this investigation attaches more attention on the structural effect on rockbursts, which tends to appeal to practising engineers.

KEYWORDS

Rockburst dynamics, Inherent rockburst, Induced rockburst, Pillar, Hard rock mining

ARMA 15-0207

Rock Mechanical Design of Gas Storage Caverns in the Salt Dome Edge Region

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In recent years, the number of new and planned gas storage caverns has increased, so that optimization of the existing salt deposits and especially the question of the minimum allowable distance between the cavern and the salt dome boundaries became important. Although caverns were built in the salt dome boundaries in recent years, however, no dimensioning concept was previously published worldwide.

This paper deals with creating a concept for rock mechanical dimensioning of gas storage caverns in the salt dome edge area. Within this dimensioning concept it has to be demonstrated that caverns can be operated gas tight and stable in this location. The analysis of the formation of salt deposits and possibilities of exploration of a salt dome represents an important basis for the model buildup and evaluation of a cavern in the salt dome edge region.

A numerical model is created that takes into account the essential and non-negligible influences in the salt dome edge area. Furthermore time-dependent, thermo-mechanical coupled numerical calculations are carried out. The influences of different model variations are going to be analyzed regarding the cavern surrounding stress state.

Based on the calculation results, the effects of varying the parameters on the cavern surrounding stress state are going to be discussed and assessed. Here, the dimensioning parameters maximum and minimum internal pressures as well as the pressure change rates of the cavern are analyzed for a cavern in salt dome edge region. An important role for the evaluation of the stress state of the cavern in the salt dome edge region plays the stress intensity index of the rock salt which is described as the ratio between the existing deviatoric stress to the short term strength of the rock salt.

Within this paper a dimensioning concept is shown which includes beneath the recommendation for the selection of a suitable calculation model of a cavern in the border region of a salt dome a dimensioning parameter as a recommendation for the minimum distance between the cavern wall and the salt dome boundary.

ARMA 15-0396

Design and Construction of a Deep Excavation in Extremely Poor Rock Mass

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[1]*Parsons Brinckerhoff*

The current in-progress bored 44-foot diameter double deck highway tunnel across the Bosphorus Strait in Istanbul, Turkey, required a deep excavation adjacent to the strait on the Asian side of the waterway, for launching the tunnel boring machine and initiating NATM tunnels at two headings on the opposite end of the excavation. The strait was formed by historic tectonic forces, leaving the Trakya Sandstone bedrock folded, faulted, intruded, intensely fractured and weathered. The excavation, 82 to 113 feet wide, 120 feet deep, and 570 feet long, included eight exploratory borings in the design process. These borings resulted in many core runs with zero core recovery. Where there was core recovery, the RQD was often zero, resulting in very few testable pieces of core. The core was evaluated also using Q, RMR and GSI procedures for evaluating rock mass quality for comparison to other excavations in the project vicinity. The rock mass was not only very poor quality, but variable quality within any particular boring (see figure below), and highly variable between borings. It was necessary to consider not only this site exploration, but other excavation experience in similar ground near sea level in Istanbul to develop reasonable and realistic geotechnical design parameters. A two-level ground support system was installed which consisted of an upper level of secant piles and a lower level of spaced bored piles, with tensioned tieback anchors and reinforced concrete walers (see figure below). After unexpectedly high lateral wall movements were measured during the initial excavation stages, the design parameters were modified and additional levels of anchor supports were installed. Following the design revisions, the excavation was successfully completed and the TBM was launched in April 2014.

ARMA 15-0615

On the Tunnelling in the Weak Slate Formations in Taiwan

K.J. Shou[1], C.L. Lee[1]
[1]*National Chung-Hsing University*

To enhance the application of the green energy in Taiwan, the Wanta-Sunglin hydropower project was executed, with a 5, 947m-long tunnel passing through metamorphic slate formations constructed by NATM method. Before the breakthrough of this tunnel in 2011, due to the difficult geological conditions, the excavation was blocked by shear zones with squeezing and creeping effects, until remedial measures and supporting adjustment were applied. Besides the difficult geological conditions, part of the alignment of this tunnel underpasses the Chuoshui River, which makes the support design even more challenging (see Figures 1). This paper summaries the support designs, the tunnel deformation instrumentation, and the feedback analysis. In addition, the treatment and reinforced adjustment for the sections of river underpassing and shear zones were also illustrated and discussed.

As it is difficult to obtain the representative samples to obtain the design parameters, the overestimation of parameters could induce the underestimation of the deformation. Adjustment of parameters with instrumentation measurement of feedback analysis is necessary for a better numerical analysis. This study not only presents a case study but also illustrates a practical way of engineering analysis for tunneling in difficult geological conditions.

ARMA 15-0162

TBM Tunneling in Discontinuous Rock Masses

zixin zhang[1]

[1]Tongji University

With the application of TBM in the construction of tunnels, increasing simulations are taken on TBM tunnels. This paper proposes the concept of utilizing block theory to simulate TBM tunnels in discontinuous rock masses and predicate the stability of surrounding rock blocks in TBM tunnels for the first time. Besides, the basic theory of the simulation on TBM tunnels with the block theory will be established through three parts: simplification of thrust and torque from the cutterhead, block classification of TBM tunnels and simulation on the excavation progress. Furthermore, an object-oriented computer model was constructed for TBM tunneling in three-dimensional multi-block systems based on the object-oriented programming (OOP) technique. The intricate structures of machine-rock rock stability interaction are deciphered by implementing object-oriented analysis (OOA), and a universal class library is developed through object-oriented design (OOD). The computer model can be created by cutting a computational domain into machine-element-blocks and then combining them into machine-complex-blocks (convex or concave). The established computer model would be highly available for TBM tunneling in discontinuous rock masses. A computer program BLKLAB is developed based on the proposed method and a case study is done on a large-scale rock tunnel.

Keywords: TBM tunneling, block theory, block classification, discontinuous rock mass, BLKLAB

Technical Session 12 – Elizabethan CD
Reservoir Geomechanics

Monday, June 29, 2015, 02:00 pm - 03:30 pm

Chairs: Gang Li & Hong Li

ARMA 15-0008

Horizontal Stress Modeling of Successively Built-up Formations: The Effect of Viscous Relaxation and Depth-Dependent Hardening

Tobias Hoeink[1], Wouter van der Zee[1], Daniel Moos[1]

[1]Baker Hughes

When estimating the magnitude of horizontal stresses, elastic properties are often assumed constant over geologic time. In addition, the successive build-up of a formation and its burial history are often not considered despite playing an important role.

In this paper, 2D finite element analysis is used to model the successive build-up of a formation with visco-elastic material that hardens with depth. Zero lateral strain and extensional lateral strain boundary conditions are explored. In all of the cases the horizontal stresses are lower than the vertical stress. Effective stress ratios are elevated in visco-elastic cases compared to elastic reference cases.

The ability of a visco-elastic material to dissipate deviatoric stresses may cause the variations in effective stress ratios imposed by layers with different Poisson's ratios to be much less pronounced than in corresponding linear elastic models. Extensional lateral strain boundary conditions lead to further reduced vertical to horizontal effective stress ratios because of reduced lateral confinement. These two mechanisms, viscous relaxation, which equalizes stress, and extensional lateral strain, which decreases horizontal stress, may operate simultaneously to determine the resulting magnitude of the horizontal stress and of the effective stress ratio. Depending on the stress regime, they may work in concert with or in opposition to each other.

In the cases considered here, variations in horizontal stress magnitudes are smaller than predicted by linear elastic models, and thus hydraulic fractures may be less confined within low-stress intervals than customarily predicted. We present here a new method to quantitatively predict horizontal stress magnitudes that incorporates this effect and that not only fits the results from the numerical models but also can (potentially) be applied to other models and to the field.

ARMA 15-0342

Investigating the Evolution of Polygonal Fault Systems using Geomechanical Forward Modeling

Daniel Roberts[1,2], Tony Crook[3], Joe Cartwright[4], Matthew Profit[1]

[1]Rockfield Software Ltd, [2]Cardiff University, [3]University of Leeds, [4]University of Oxford

The genesis and evolution of Polygonal Fault Systems over geological time remains poorly understood despite detailed study using 2D and 3D seismic data. Polygonal faults are thought to present shallow drilling hazards and potentially compromise the integrity of regional caprocks. PFS contain networks of exclusively normal faults that intersect bedding planes at a wide variety of azimuths. This fact alone suggests a non-tectonic origin and recent arguments focus on a constitutive control on PFS formation.

Geomechanical forward modelling has the potential to shed light on the evolution of material and stress state as geological structures form. The evolution of polygonal faults is studied here using the finite strain forward modelling code *ELFEN*. More specifically the recently suggested diagenetic trigger for PFS formation is investigated, and the process of incorporating this into a critical-state based model is outlined and discussed. The results demonstrate the formation of PFS in both 2D plane-strain and full 3D simulations as validation of both the genetic argument and the computational approach.

PFS are additionally observed to be sensitive to subtle horizontal stress anisotropy e.g. around salt diapirs or larger tectonic faults. As such, there is the potential for these fault networks to act as 'paleo-stress piezometers'. This study investigates this by incorporating subtle stress anisotropy into the model and observing the influence on fault alignment. Results indicate that even for subtle stress anisotropy, preferential fault alignment is observed and this is consistent with observation.

ARMA 15-0426

3D Modeling of Sand Production in Waterflooding by Coupled Flow/ Geomechanical Numerical Solutions

Mohammad Nassir[1], Dale Walters[1], David Yale[2], Robert Chivvis[3]

[1]Taurus Reservoir Solutions Ltd., [2]Exxon Mobil Upstream Research Company, [3]BP Exploration (Alaska) Inc.

Sand grains can be dislodged and mobilized when exposed to high fluid flow drag forces in the production of poorly consolidated sandstone hydrocarbon reservoirs. The phenomenon is called sand production and might be beneficial in terms of permeability enhancement around the wellbore; however in some real field operations the drawbacks outweigh the benefits. Erosion and clogging of wellbore tubulars, production lines and surface equipment, and premature breakthrough in waterflooding practices are some of the problems resulted from uncontrolled sand production.

The complex physics of sand production can be better understood by modeling the pressure gradients associated with multiphase fluid flow, stress variation along with shear/ tensile failure around the induced dilated zone and the dilated zone propagation under certain critical conditions. In the current study, an explicitly coupled 3-D multiphase flow/ geomechanical simulation software is implemented and developed to model the dilated zone propagation resulted from the produced sand. Yale et. al.[1] criterion for sand production has successfully been implemented to allow a certain numerical element join the main dilated region. The force balance criterion calculates the threshold fluid pressure gradient based on the confining stresses acting on a numerical element. If the fluid pressure gradient exceeds the threshold, it switches the element to a cavity with no load bearing

capacity. The stress variation across the loosely supported sand body at the edge of a dilated zone is captured by an elasto-plastic constitutive model in which the stress variation over the Mohr-Coulomb shear failure surface is honored.
Applying the model to some example problems reveals interesting results about the complex nature of sand production in waterflooding operations. From stress solution point of view a slight dilation in sand structure (~10% increase in porosity) makes the whole body unloaded and similar to a fully cavitized void. The dilated zone (or caity) geometry appears to be a strict function of the weak layer thickness. The sheared zone front moves ahead of the cavity/sand interface and it constitutes a failed plastic region within the interfaces. Small load bearing capacity of the failed region leads to formation of a low stressed strip at the cavity/sand interface and it facilitates the sand production by fluid pressure gradient. Multiphase flow, over vs under-injection, and interwell pressure gradient effects are the key in controlling the sand production initiation and evolution. The results of the current study can help understanding the significance of different mechanisms contributing the sand production in order to mitigate the premature breakthrough problem in real field waterflooding practices.

ARMA 15-0801

Matching 4D seismic time-shifts in structurally complex overburdens with 3D geomechanica models

Atef Onaisi[1], Julien Fiore[1], Adrian Rodriguez-Herrera[2], Nick Koutsabeloulis[2], Federico Selva[1]
[1]Total, [2]Schlumberger
Subsurface pressure and temperature variations can alter rock properties both near and relatively far from the disturbance, causing detectable changes in seismic travel times. In modelling such phenomena, we employ large-scale geomechanical simulations to translate reservoir depletion into subsurface deformations that account for overburden heterogeneity and heavy faulting patterns derived from seismic interpretation. Subsequent velocity perturbations are then obtained using strain-dependent stiffness perturbations from nonlinear elasticity theory. By applying this methodology to a channelized turbidite reservoir located in offshore West Africa, we show that appropriate calibrations can generate geomechanically-based overburden time-shift predictions that reproduce signatures from an actual 4D seismic monitor survey, thus providing valuable insights into reservoir pressures, rock compressibility and fault stiffness. The results also demonstrate the importance of integrating non-homogeneous overburden descriptions in successfully explaining many 4D seismic signatures.

ARMA 15-0219

A Comparison of Stress Evolution in Single-layer and Multilayer Buckle Folds

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Buckle folds of single-layer and multilayered sedimentary strata characterized by associated fractures are among the most common structural traps for hydrocarbon reservoirs. The spatio-temporal evolutions of the pore pressure and stress state in folded reservoirs are of significant importance for the understanding and predicting various patterns of fracture associated with buckle folds. This paper compares the evolutions of pore pressure and stress state associated with buckle folding by studying the deformation process of two different geometries: single-layer and concentric multilayer buckle fold under the condition of realistic in-situ stress. A 3D finite element modeling approach is applied to simulate the buckle folding of single-layer and multilayer stacks with Maxwell visco-elastic rheology. The influence of various parameters including overburden depth, competence contrasts, viscosity, and permeability are considered. The numerical simulation results demonstrate that these parameters are critical for the pore pressure evolution and the initiation of different fracture systems in the single and multilayer buckle folds to varying degrees. It is concluded that the pore pressure and stress state within the folding layer(s) are determined by the buckling process, fold geometry and material parameters. The development of abnormal pore fluid pressure is found to depend on the strain distribution and permeability during compression of the folded layer(s). For

single-layer buckle folds, the stress evolution indicates that fractures at the hinge zone are mostly due to low permeability (<10-19 m2), high viscosity (≥1021 Pa s), and low overburden pressure, while the limb fractures mainly result from a combination of compressional buckling and erosion/exhumation. The results further show that the multilayer geometry amplifies the initiation likelihood of tensile fracture at the hinge zone of the central layer by reducing its dependence on material parameters. In comparison with single-layer fold, the zone between the hinge and limb of the central layer in the multilayer system is found to have the highest potential for the initiation of shear fractures. In summary, the evolution of pore pressure and stress state in fold systems are determined by the strain history along with the distribution of material parameters, and that a multilayer geometry provides a more general explanation for the fractures associated with buckle folds.

ARMA 15-0469

Assessment of stress changes in hydrocarbon reservoirs using analytical methods

Roberto Quispe[1], Pedro Firme[1], Deane Roehl[2], Luis Paullo[2], Miltiadis Parotidis[3], Ana Domingues[3]

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Assessment of stress paths in ellipsoidal and cylindrical hydrocarbon reservoirs using analytical methods

This paper focuses on the assessment of stress paths in ellipsoidal and cylindrical hydrocarbon reservoirs. Analytical solutions for these reservoir shapes are presented and discussed. For ellipsoidal reservoirs, Rudnicki's solution is preferred, since it can take into account some important issues, such as the arching effect and the contrast of properties between reservoir rock and surroundings. For cylindrical reservoirs a new method is presented based on Geertsma's solution and the Finite Difference method. An extension of Geertsma's model to consider spatial pore pressure changes and different reservoir shapes has been developed in previous studies. However, this solution cannot assess results inside a depleted reservoir. In order to get an indication of what is happening in this region, some authors take linear interpolations of the displacement at the boundaries of the reservoir to represent results inside it. This implies uniform changes in strains and stresses inside the reservoir, which is true for ellipsoidal reservoirs. However, inside cylindrical reservoirs, different displacements, strains and stresses can be developed. To overcome this limitation, closed formulae to assess the displacement field inside the reservoir are presented in this paper. With this accurate displacement field and an appropriate Finite Difference Scheme, changes in strains and stresses can be determined, allowing the assessment of analytical stress paths inside cylindrical reservoirs. This new method, herein called "Modified Geertsma's solution", has been implemented and validated through different synthetic models using the Finite Element Method. The results are discussed through the identification of different geomechanical behaviour inside and outside ellipsoidal and cylindrical reservoirs. The advantages of the proposed method compared to the traditional and simplistic uniaxial solution is shown.

Poster Session I:

PET-P-01: Monday, June 29, 2015, 03:30 pm - 04:30 pm

ARMA 15-0028

Behavior of salt from the Bayou Choctaw salt dome

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The Bayou Choctaw salt dome, located in southeastern Louisiana, is home to one of four underground oil-storage facilities managed by the U. S. Department of Energy Strategic Petroleum Reserve (SPR) Program. Sandia National Laboratories, as the geotechnical advisor to the SPR, conducts site-characterization investigations and other longer-term geotechnical and engineering studies in support of the program. As part of this program, an experimental effort was completed to

better characterize the salt strength, dilational strength and creep resistance in the salt section above Cavern 102 and below the overlying abandoned caverns, where casing issues have been observed. Data from these tests will be used to inform numerical analyses as well as extend our understanding of the mechanical behavior of this salt.

Short-term mechanical tests were performed under axisymmetric compression and axisymmetric extension stress states at ambient temperature (22-26 C). Creep tests were performed at constant differential stress with a confining pressure of 7.6 MPa and at a temperature of 38 C (conditions representative of the core depth). Specimens used for the axisymmetric compression and creep testing were nominally 101.6 mm in diameter (core diameter) and 203.2 mm in length. Axisymmetric extension specimens measured 69.9 mm in diameter and 139.7 mm in length and were smaller than the compression specimens due to restrictions of the testing system.

Tests indicated that the dilation criterion developed from axisymmetric tests is both pressure and stress state dependent. As the mean stress applied to the specimen increases the shear stress required to initiate dilation increases as well. Results obtained for this salt are reasonably consistent with results for other domal salts. It was found that under axisymmetric extension conditions less shear stress was required to cause dilation as compared with the axisymmetric compression stress state for the same mean stress. This is also consistent among other domal salts. The average Young's modulus for the salt was found to be 44.4 GPa, and Poisson's ratio averaged 0.30. With an assumed activation energy of 10,000 cal/mol creep tests showed that this salt is intermediate in creep resistance when compared to other bedded and domal salts. The power-law creep relationship for Bayou Choctaw salt was determined to be:

$$\dot{\varepsilon}_{ss} = 4.08\times10^{10}\left(\frac{\Delta\sigma}{\mu}\right)^{4.07}$$

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ARMA 15-0036

Experimental Investigation on the Effect of Pore Pressure on Rock Permeability-Bakken Formation Case

Jun He[1], Kegang Ling[1], Peng Pei[1], Xiao Ni[2]

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The conventional petroleum reserves are depleting significantly on a worldwide basis. In order to meet the demand for hydrocarbon energy, it is essential to develop unconventional resources. Over the past decade, shale oil becomes an important source of oil across the North America. Bakken Shale oil, one of the largest shale oil plays in the world, is producing about 1 million barrel oil per day. The main methods exploiting Bakken oil are drilling horizontal wells with multi-fracturing technology. Although initial production rate after fracturing is high, the oil rate declines rapidly. This decline is in part due to the deterioration of permeability resulting from the depletion of reservoir. Unfortunately, it is only known in general that permeability declines as pore pressure is reduced. There is no a database that relates the evolution of permeability with depleted pore pressure available. Without a permeability-pore pressure correlation developed from experimental data engineers and geoscientists cannot evaluate the relationship between permeability and pore pressure confidently.

To better understand the effect of pore pressure on rock permeability, it is imperative to obtain experimental data to develop a reliable correlation. In this study, core samples from Bakken formation were analyzed. For each core sample, rock permeability at different pore pressures were measured while holding the confining pressure constant. After that permeability at different

confining pressures were measured. Experiments measured more than 100 Bakken samples. Therefore, the test result provided a large database for the analysis of Bakken formation properties.

The significances of this study are: (1) obtained rock permeability versus pore pressure data sets for Bakken formation, which include very low to relatively high permeability rock; (2) measured data can be incorporated into reservoir model to simulate the reservoir performance to accurately forecast production from Bakken; (3) provided a correlation to calculate permeability as a function of pore pressure; (4) served as a guidance in analyzing other shale gas and oil plays whose reservoir characteristics are similar to Bakken formation.

ARMA 15-0089

Optimum Condition of Hydraulic Fracture-Natural Fracture Interaction in Shale Block Experiments

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Natural fractures serve both as the reservoir space and the flow channel of fluids in shale gas reservoirs, whose low permeability requires large-scale hydraulic fracturing to build a more complex fracture system to extract gas. Numerous researches have been conducted on the interaction between hydraulic and natural fractures based on both experimental and numerical investigation. Fracture interaction criterion was derived to predict whether the induced fracture would cause shear slippage on the natural fracture plane which leads to arrest of the propagating fractures, or dilate the natural fractures that cause excessive leak-off. The interaction between natural fractures and hydraulic fractures were observed in blocks of natural shale outcrops by a series of Tri-axial tests, which revealed how parameters work on hydraulic fracture geometry, mainly including natural fractures and the brittleness index. The results show that shear-slip deformation, through which the permeability of the natural fractures could be enhanced, could be easily made by hydraulic fracturing with a specified reduction in the effective stress, interfacial cohesion or internal friction angle. With a certain stress difference and crack occurrence, smaller approaching angle, higher pump rate and lower fracturing fluid viscosity would contribute to the bigger stimulated volume in shale formation. The complexity of fracture network also attribute to the high brittle deformation of the formation. Optimal shale target would be low strength and hardness but high brittleness. Hydraulic fractures appear to grow roughly parallel to the maximum stress and experience a temporary deviation along the pre-exsiting fractures but then re-orientate for the dominance of maximum stress. Based on the laboratory results, we propose a criterion for depicting the fracability of the reservoir, which could be much more practical for the formation evaluation and the better fracture initiation.

ARMA 15-0102

Proppantand host rock deformation in fractured shale flow through experiments

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A series of preliminary tests have been performed on manually fractured and propped shale. These tests are a precursor to laboratory scale hydraulic fracture and proppant tests to investigate the placement of proppant within the fracture and the effectiveness of the proppant at maintaining permeability within the specimen. Currently, proof of concept tests are underway on the hydraulic fracture system. Tests will be used to inform proppant flow models which seek to model proppant density and distribution within a fracture.

The shale used in the study contained 5-10% porosity, and 10-40% clay. Samples were fractured subparallel to bedding. Proppant was manually distributed between fracture faces resulting in a monolayer with a random distribution. The proppant used was #20-30 sieve quartz sand. Specimens were repeatedly subjected to example reservoir conditions (20.7 MPa confining, 6.9 MPa differential stress and 75°C). Permeability of the specimens was determined during testing by flowing DI water through the specimen at a rate of 0.002 ml/min, with the downstream line open to atmosphere. Upstream pressures varied as necessary to maintain the flowrate, and at its highest was approximately 1.4 MPa. Between testing periods the specimen was removed and scanned using x-ray micro computed tomography (CT) with an effective pixel resolution of approximately 40-55 microns per voxel.

A noteworthy decrease in flow rate was observed in subsequent test periods due to fracture closure. Fracture closure, as observed with CT scans was accomplished by a combination of clay swelling, proppant embedment, proppant fracture, fines migration, shale wall spalling, and rigid body translation. All of these contributed to a reduction in the effective fracture aperture. The fluid flow contributed to clogging of flow paths due to particle transport. It was also noticed that when grains were isolated they tended to crush whereas areas with arrays of grains in close proximity grains fracture less and tend towards embedment.

Numerical simulations based on the actual crack geometry are underway to address the effect proppant particle placement and closure on flow. Actual crack geometry is developed from CT scans of the specimens then particles are placed with various computational approaches which are then meshed for flow analyses via the finite element method. Preliminary results will be discussed.

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ARMA 15-0106

Exploring Conceptual Models of Hydraulic Fracture Network Growth

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Three conceptual models for complex fracture network growth due to hydraulic fracturing (simple geometry, PFSSL, and MMS) were explored using discrete fracture network simulation. Simple geometry models, variants of which are commonly used in industry, neglect the effects of natural fractures present in the reservoir pre-stimulation. PFSSL (primary fracture with shear stimulated leakoff) and MMS (mixed-mechanism stimulation) are alternative models which account for interactions between natural and newly formed hydraulic fractures. The investigation centered on finding physical consistency with the parameters of fracture network length, stress and heterogeneity effects, and pressure trends. It is found that simulations of the simple geometry model yield results that are not physically realistic, while results of PFSSL and MMS simulations show better correlation with experimental data, including fracture length and geometries predicted by microseismic studies. This study uses CFRAC, a leading 2D simulator of fracture network growth that efficiently couples fluid flow and geomechanical deformation in low-permeability reservoirs.

ARMA 15-0125

Analysis of Stimulated Volume Resulting From Fluid Injection into a Fracture Rock Mass

Alexander Verde Salas[1]

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Natural and hydraulic fractures in shale reservoirs are essential for providing transport conduit for the movement of fluids during fluid injection and extraction. Variations of flow conditions in the reservoir induce tractions on the fractures that potentially cause a joint to slip or micro-earthquake (MEQ) when the shear stress exceeds a critical value based on a failure criterion. Proper identification of subsurface events in a large-scale situation is of great interest for the geothermal and petroleum industries to monitor potential modification of fracture permeability during production operations as well as hydraulic fracture propagation in stimulation treatments. The Displacement Discontinuity Method (DDM) is commonly used for modeling the behavior of fractures in linear-elastic rocks. However, DDM requires the calculation of the influences among all fractures, so it is not computational efficient for large fracture systems. This work involves using the Fast Multipole Method (FMM) with DDM to simulate large-scale naturally fractured reservoirs subjected to production and injection. Synthetic case studies containing up to ten thousand fracture elements in reservoirs with and without sealing faults are carried out and the microseismic responses analyzed. The results show the approach to be effective and efficient. In addition, the results do illustrate the role of the fluid pressure on the fracture failure mechanism in large-scale situations. Finally, fractured reservoirs with faults experienced more events due to the compartmentalization that causes zones of higher pressure to develop.

ARMA 15-0197

Coupled Numerical Simulation of Formation Rock and Cement Sheath Effect on Vertical Cased Well Fracturing

Xiaoyu Du[1], Yan Jin[1], Mian Chen[1], Yunhu Lu[1], Zhi Geng[1], Hailong Jiang[1], Yayun Zhang[1], Henglin Yang[2]
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In the casing well, cement sheath is mainly used to support casing, seal off annulus, isolate porous zones respectively, and protect the casing from corrosive formation fluids. During the production period, the integrity of the casing–cement–formation system is generally dampened by perforation and fracturing process, leading to failure of fracturing operation. Previous Studies on cement sheath rarely involve the coupled simulation applied to hydraulic fracturing, gaining scarce industrial experience.
In this paper, coupled numerical simulation of fracturing process in casing well is done using FLAC^{3D} (Fast Lagrangian Analysis of Continuain in Three Dimensions), analyzing the effect of formation and cement sheath on the integrity of the casing– cement–formation system. A model of deep casing-cement-formation system is proposed according to in situ conditions, the upper strata is loaded with equivalent stress, the rock and casing in fracturing section is simulated using physical model, using Mohr-Coulomb failure criterion. The geological interfaces are comprised of interface units, which are non-thickness contact element suited for the Coulomb Shear Constitutive Model in FLAC^{3D}. In order to refine the failure process of cement sheath, step loading of 10 MPa is applied.
It appears that cement with low Young's modulus and high Poisson's ratio is crucial to retain the integrity of the casing–cement–formation system. Fracturing operations should be initiated in sections of cements with lower Young's modulus and higher Poisson's ratio, and formations with higher Young's modulus and lower Poisson's ratio.
The coupled model proposed can gain insight into interaction effect of casing metal, cement and rock, optimize the design of perforation operation for reservoir stimulation in casing wells, having long term influence on reservoir ultimate recovery.
Keyword：Cement sheath ；Casing well ；Coupled model ；Numerical simulation ；FLAC^{3D}

ARMA 15-0206

A Case Study for Wellpath Optimization and Drilling Risk Reduction for Vaca Muerta Shale in Argentina

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The Vaca Muerta formation of the Neuquen Basin is an emerging shale play with extensive lateral extent and thickness up to 300 m with significant anisotropy and heterogeneity throughout the basin. In situ stress analysis obtained using drilling induced tensile fractures and breakouts indicates a steadily oriented stress tensor and principal stress magnitudes consistent with the normal faulting stress regime. Analysis of a wellbore stability study conducted using the drilling and well logging

from the limited number of wells drilled imply that horizontal wells drilled in the direction of the North-South in Vaca Muerta field are the most stable and productive wells.
In this study, an integrated wellbore-integrity study was utilized to solve wellbore instability events including stuck pipe and tight holes encountered during the drilling of the recent wells, to optimize future drilling operations, to maximize the drilling margin for the prospective wells, and to reduce drilling risks in the field. The geomechanical model was coupled with the in-situ stress and formation property anisotropies, temperature alteration, shale-fluid physico-chemical interactions, and the flow-induced stress using the Mohr-Coulomb and Mogi-Coulomb failure criteria. The possible causes of the wellbore instability issues have been identified. The well trajectory, drilling-fluid density, and types of water-based mud were confirmed to have a dominant impact on the occurrence of the wellbore instability problems experienced in drilling and completion of the Vaca Muerta formation. Core data, imaging and sonic scanner logs along with conventional log data were utilized to obtain in-situ stress magnitudes, orientations and formation properties. The stochastic risk and sensitivity analysis were conducted from thirteen wells to evaluate the sensitivity of the obtained input data on the study outcome.
The results show that a slightly heavier drilling fluid with an increase of 0.1 gr/cc from the mud weights currently used in the wells analyzed is expected to minimize the instability issues. The results of the wellbore integrity analysis presented in this study will benefit the remediation and/or prevention of wellbore instability issues for improving economic viability and sustainability of the field development in the Vaca Muerta Formation.

ARMA 15-0216

Numerical Calculation of Fault Reactivation and Resultant Seismic Behavior Related to Cuttings Reinjection in Offshore West Africa

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Drilling cuttings reinjection has the potential to influence fault reactivation and seismic activity, when reinjected in proximity to a fault. Engineering design of the cuttings reinjection execution must incorporate this potential into the design.
In this study, the poroelasto-plastic finite-element method (FEM) is used to calculate a set of scenarios of values of injection pressure under which fault reactivation could occur. Seismic activity related to this fault activation is calculated using an analytical method with a numerical solution of displacement discrepancy across the fault as input. Maximum magnitude of the seismicity induced by this fault reactivation is calculated.

Fault reactivation under given injection pressure is estimated for faults surrounding a well designed for the purpose of drilling cuttings reinjection in offshore West Africa. This well is in a block bordered by three major faults. The results of these calculations of fault reactivation and seismicity are used to design the injection pressure and control the total volume of drilling cuttings that can be safely injected.

The fault being investigated is in the maximum horizontal stress direction of the field to the injection well. The following assumptions are adopted in the calculation: the pore-pressure boundary condition at the bottom of the fault is determined by the injection pressure, which is given as input data, and the inclination angle is 70°.
The FEM being used is a simplified plane-strain model (see Fig. 1). The bottom of the fault is at TVD = 2,050 m, and is assumed to be connected with the front tip of the fracture. The height of the model is 600 m, and its length is 1,000 m, with surface pressure applied on its top as overburden. Three kinds of materials are used. The material representing the fault has higher permeability and low stiffness and is a Mohr-Coulomb-type plastic material. A set of different values of cohesive strength and internal frictional angle are assigned to the model to see both the worst and the best scenarios for fault reactivation.

Numerical results obtained with the FEM model include the distribution of the equivalent plastic strain within the whole model, distribution of the von Mises equivalent stress, and the area of the displacement field under the specified pore-pressure boundary conditions at the bottom of the model. The area of the plastic region is the place where the fault is being reactivated. In this way, results showing both the location and level of fault reactivation are obtained and can be visualized.
Numerical of result of displacement discrepancy across the fault is used as input of seismicity calculation. Shows the pore-pressure distribution along the fault (left) together with the distribution of displacement field (right) of the model at the stage when the fault is activated.

This work presents a best practice for estimation of fault reactivation and magnitude of seismicity caused by cuttings reinjection.

ARMA 15-0256

The Effect of Desorption-induced Porosity-Permeability Changes and Geomechanics on Production from U.S. Shale Gas Formations

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Shale gas reservoirs are organic-rich and fractured rocks which are characterized by ultra-low permeability and porosity. Recent experimental studies show that methane gas desorption phenomena is important and should be considered in modeling of shale gas production. Nevertheless, the subsequent changes in porosity, permeability, and stress state due to methane desorption have not been captured in current shale gas modeling and reserves estimation. Hence, it is very critical to investigate the effects of induced stress, porosity, and permeability by methane desorption on gas production for major shale plays in the U.S.
Six major U.S. shale gas reservoirs are considered in this study including Utica, Marcellus, Barnett, Haynesville, Eagleford, and New Albany shale. In this work, a simple reservoir model that divided the shale reservoir into three zones, hydraulic fractures, induced fractures and unstimulated zone is proposed which accounts for shale matrix desorption and geomechanics of hydraulic fractures. Derived formulas to correct for porosity and permeability are implemented in the proposed model based on thermodynamic desorption isotherms and geomechanical volumetric strains. Moreover, a sensitivity study is performed to identify the most controlling parameters to long-term gas production from the investigated shale reservoirs using the proposed model.
The result showed that a significant overestimation of gas production and reserves estimation is encountered by neglecting porosity and permeability corrections. This error was estimated about 30 to 150 percent in original gas in place (OGIP) for the investigated shale reservoirs based on history matching of real field data. The sensitivity analysis revealed that fracture half-length, spacing, and desorption based storativity are the most influential parameters in modeling and simulation of shale formations. This paper improves our understanding of shale reservoirs and introduces more insights into accurate modeling and reserve estimation of unconventional reservoirs.

ARMA 15-0262

Geomecanical Modeling in CO2 Enhanced Oil Recovery

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The Bakken Formation is an extremely tight formation with low porosity and permeability. Activity in developing such an unconventional play has increased due to the success of horizontal drilling coupled with multi-stage hydraulic fracturing. However, due to high capillary trapping the primary recovery factor in the Bakken remains rather low. Therefore, small improvements in productivity of Bakken wells by applying enhanced oil recovery could increase the recoverable oil by billions of barrels. Among several EOR options, CO_2 flooding may be effective to increase the recovery factor.
In this paper, numerical simulation is used to evaluate the performance of CO_2–EOR for the Bakken Formation. Different scenarios of CO_2-EOR are tested to compare the effects on oil recovery. They are: well patterns, continuous versus cyclic injection, injection gas composition, and heterogeneity. There is also a strong interest in coupling reservoir fluid flow with geomechanics to

study the stress and deformation of reservoir rock thoroughly. The main focus of this work is using the coupled code between reservoir flow and geomechanics to study the deformations, CO_2 storage, and enhanced oil recovery in the Bakken Formation under different strategies.

ARMA 15-0268

Brittleness Determination of Rock Using Rock Physics Techniques Calibrated With Macro Damage

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Rock brittleness is an indicator to characterise the intensity of failure, widely used in shale hydraulic fracturing for reservoir stimulation, nuclear waste repository and tunnel construction.
Practical measurement approaches of brittleness are reviewed. A brittleness determination method comprised of rock physics techniques and mechanical tests is proposed for dry samples of shale, sand, carbonate rock and concrete with different sand content. The samples are tested with ultrasonic pulse under hydrostatic pressure, then the dynamic elastic parameters of intact samples without artificial damage are inversed using filtered sonic signals. Triaxial tests of samples are carried out under various confining pressure with constant temperature, recording stress-strain relations and AE (acoustic emission) signals originated from macro rock damage. Static elastic parameters of samples are hence determined and correlated with dynamic parameters. The method for brittleness determination is presented afterwards, with comprehensive consideration of pre-peak damage of stress-strain curve and post-peak energy release rate.
It appears that the method, which revealed intrinsic brittleness of intact samples and failure under artificial load, appropriately characterizes brittle behavior of rock with matrix damage. The brittleness of shale is far more brittle than other samples used for tests. The shale samples shows ductile behavior along with rising confining pressure. The SEM (scanning electron microscope) image of failure shale samples shows cracks of brittle failure under test load in rock matrix. The chemical element analysis of rock matrix beside the cracks indicates that quartz, a kind of brittle mineral, abounds.
With sufficient laboratory tests of samples, the method proposed can predict brittle behavior of underground reservoir rock and engineering rock mass with different lithology using geophysical techniques and datasets, providing practical engineering guidance.

KEYWORDS: brittleness, triaxial test, ultrasonic pulse, SEM, acoustic emission

ARMA 15-0274

Numerical Simulations on the Motions of Supercritical Carbon Dioxide Jet and Its Abrasive Particle

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Massive hydraulic fracturing (MHF) is one of main means in shale gas reservoir development. But it is a high-cost and high-risk task to execute MHF operation in most of China where massive water us is impratical. Breakthrough on the non-water fracturing technologies is in urgent need, it was raised in 2004 that supercritical carbon dioxide (SC-CO2) fluid could be used in hydraulic fracturing in shale gas reservoir instead of water. However, viscosity of SC-CO2 fluid may as low as one tenth of that of water and thus, particle carrying capacity of it and feasibility of abrasive SC-CO2 jet technique are remained to be proven.
Using the computational fluid dynamics method, models for three-dimensional jet flow field were builtand calculations were carried out via mainly investigating the motions of jet fluid and single particle. Velocity distribution laws of jet fluid and single abrasive particle through the computational domain under different fluid jet, fluid temperature and particle diameter were obtained, particle carrying capacity of SC-CO2 jet was evaluated and compared with other fluids. By now, almost all the simulations and relevant discussions and analysis have been accomplished.

Results prove that: SC-CO2 jet can efficiently carry a single particle that particle can obtain almost ashigh axial velocity as jet fluid all through the computational domain; under the simulated conditions, particle carrying efficiency of SC-CO2 jet could be even higher than other examined fluids in terms of two phase velocities when jetting out of the nozzle, both jet velocity and impat velocity on the wall of particle in SC-CO2 jet are the highest compared to those in other fluid jet; rise of fluid temperature will slightly impair the particle carrying capacity of SC-CO2and particle velocity can still obtain an increase by a big margin almost equal to fluid, so dose impact velocity on the wall of particle; for the commonly used abrasive like silica sand or ceramic proppant, SC-CO2 jet is expected to carry particle with diameter of 0.1~2.4mm with a certain concentration to successfully form abrasive SC-CO2 jet, in addition, the larger the diameter is, the higher the impact velocity is.
The research on using SC-CO2 jet into petroleum industry is novel and still at a start-up stage, not to mention the abrasive SC-CO2 jet, with no media reported or literature and research findings documented. SC-CO2 fluid, with high solubility to hydrocarbons and no damage to pay zone, is expected to extract more yield per well. Relevant numerical simulations and experiments on the abrasive SC-CO2 jet will be soon followed. The results would be of great theoretical guidance and reference value for the experiments and practical applications in the future.

ARMA 15-0300
Capturing Early Evolution of Salt Openings

Frank Hansen[1], Cliff Howard [1], Kris Kuhlman[1], John Holland[1]
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In situ tests implemented in an underground facility mined from salt deposits, if planned appropriately, provide an opportunity to characterize the host rock before, during, and after excavation of test rooms. Characterization of the test bed is essential to interpret structural deformation, formation and evolution of the disturbed rock zone, and measurement of first-order properties as the salt evolves from an impermeable undisturbed state to a more-transmissive state. The strategy expounded upon in this paper describes recommended geophysical measurements to characterize the initial state of the test bed and its evolution over the course of an underground test. Discussion includes what measurements could be made, why the measurements would be made, how they are made, and how accurately they need to be made. Quantifiable parameters will establish field-scale boundary conditions and data quality objectives to characterize the test bed in an underground salt research facility.

Principal measurements make it possible to monitor geomechanical response and the associated changes in permeability. This progression will help establish boundary conditions for whatever activity is conducted within the excavations. Pretest predictions of the response include strain magnitudes, room closure, and margins of the damaged zone. In turn, evolutionary measurements themselves will allow assessment of the predictive capability. Geomechanics modeling provides a basis for data quality objectives, which help define instrumentation requirements. Sufficient detail is provided to install gauges, conduct tests, and describe applicable functional and test-specific requirements. This type of forward thinking provides a primary means to reach and document consensus on all aspects of a test or experiment, including design, cost, schedule, interface controls, and data management.

ARMA 15-0360

On Poroelastic Inclusions and its Applications in Reservoir Mechanics

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Geological structures in the subsurface can be simplifies as ellipsoidal inhomogeneities with different aspect ratios. For instance, one can model fractures or the whole reservoir as an inclusion by considering possibly different material properties and different fluid pressure/temperature in comparison to those of the surroundings. Hence, the stresses and displacements associated with the fluid withdrawal from (e.g. hydrocarbon production) or fluid injection into (e.g. Carbon sequestration) the formations could be determined by assuming no hydraulic communication between the inclusion and the surrounding medium. The lack of hydraulic communication could be the result of a cap rock or an impermeable seal/fault. On other hand, in the case of fractures, this assumption in not valid anymore and the hydraulic communication between the inclusion and medium should be considered in the calculations.
This paper provides analytical solutions for deformation and stress distribution inside and outside of poroelastic ellipsoidal inclusions. We combined Eshelby theory with the Biot theory of poroelasticity to model the change in stress caused by changes in pore pressure and temperature inside the inclusions. Using the provided analytical solutions, we explore the effect of different inclusion sizes, material properties and pressure/temperature condition. The results confirm that neglecting hydraulic communication between the inclusion and the sounding matrix may result in large differences in mechanical response of the inclusions.

ARMA 15-0406

Field and experimental brittleness (toughness) determination of Vaca Muerta Shale.

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Rock fracability characterization is a key issue for stimulation of unconventional reservoirs. This property not only controls hydraulic fracture initiation and propagation pressure, but also affects the Stimulated Reservoir Volume (SRV) which in turn controls well productivity. Several parameters such as brittleness, plasticity and toughness, among others, are frequently referred in the literature to describe rock fracability. This paper discusses the validity of these parameters and emphasizes the validity of the linear elastic fracture mechanics approach based on the critical stress intensity factor (K_I) to characterize rock fracability.
This article presents results of experimental studies using synthetic and real Vaca Muerta shale Formation samples. Fracture Toughness (K_{IC}) was determined using notched Brazilian discs and semicircular three point bending specimens.
The influence of applied load rate, material composition and exposure conditions (air vs. immersed in different fracturing fluids) upon fracability is discussed in terms of K_{IC} and stress Corrosion Cracking Intensity Factor (K_{ISCC}) measurementsconducted on rock samples.

Keywords: Fracture Toughness, Reservoirs stimulation, Rock fracability characterization, Stress Corrosion Cracking, SCB test.

ARMA 15-0438

Screening of the EOR Potential of a Wolfcamp Shale Oil Reservoir

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Screening of the EOR Potential of a Wolfcamp Shale Oil Reservoir

In this paper a screen study was first conducted to analyze the feasibility of every EOR method for a Wolfcamp shale oil reservoir. Actual reservoir and fluid data, and field operational parameters were used. The study shows that water injection and gas injection are most feasible EOR methods. After that, a detailed simulation study was carried out to evaluate the potentials of water and gas injection. The model was calibrated with the actual reservoir performance data. Waterflooding, cyclic water injection, gas flooding and cyclic gas injection were evaluated. The results show that cyclic gas injection provides the highest EOR potential for this reservoir. A further sensitivity study was carried out to capture the uncertainties of reservoir and fluid properties, and operational parameters. Simulation results indicate that the oil recovery factor can be increased more than times by gas injection. This study provides a justification for a possible field implementation in the shale reservoir. It also provides a guide for the EOR screening in shale oil reservoirs.

ARMA 15-0537

Reducing the Uncertainty in Tight Rock Porosity Estimation by Combining Different Methods_Bakken Formation Case

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In recent years, petroleum exploration and production from the Bakken Formation in Williston Basin have gained great momentum and pushed the oil production to over one million barrels per day. However, producing hydrocarbons from the Bakken Formation is challenging due to its low porosity and permeability. Estimation of original oil and gas in place and recoverable hydrocarbons of the Bakken Formation requires an accurate estimation of porosity. In addition, porosity is one of the key parameters in modeling fluids flow in reservoir matrices. Unfortunately, uncertainty in porosity measurements in tight rocks such as Bakken could be as high as +/1.0 porosity unit if a single method is applied. This is significant considering that most Bakken sample porosity is less than 8%.

Because of the high uncertainty in measuring the porosity of tight rock, it is worthwhile to investigate porosity through different methods in order to reduce uncertainty. In this study, we measured the porosity of tight rocks utilizing four different methods: gas expansion method, radius-of-investigation method, pressure buildup method, and oscillating pulse method. The measured porosity is also compared with the well log derived porosity. The effect of confining pressure on the change of porosity is inspected. In this way, the comparability of results from different methods increased. Furthermore, difference among the results is useful for indicating the heterogeneity and/or microcracks of the rock, which are crucial in drilling and completing unconventional oil and gas wells.

Porosity of over 200 Bakken core samples have been measured in this study. The uncertainty in the porosity measurement is reduced by applying proper experiment procedures and cross-checking by different approaches. Experience and lessons learned from this study can be a good guideline to the accurate measurement of other tight rock porosity. Therefore, a more accurate evaluation of hydrocarbons in place is possible and the primary production design and enhanced oil recovery method selection can be more appropriate.

ARMA 15-0538

Analytical model of accelerating gas flow-induced conductivity damage in propped hydraulic fractures

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Hydraulic fracturing is carried out to create a conductive fracture in tight reservoirs to provide an easier path for fluids to flow to the wellbore. The flow rate that can be achieved by hydraulic fracturing has a strong relationship with the level of fracture treatment carried out. The design of fracture treatment is usually optimized to be productive as well as cost-effective. A flow rate prediction model is usually used in the design process. However, the actual performance of fractured wells is often turned down due to the loss of fracture conductivity. The inertial effects such as Forchheimer drag and acceleration are believed to the major sources for this.
In a high-pressure gas well, gas acceleration increases continuously as the gas moves and expands through propped fractures toward the wellbore. This paper presents a analytical method to model the accelerating flow effect on the production performance of hydraulically fractured wells by modifying the fracture conductivity. The method is suitable to conveniently incorporate the accelerating flow effect in a production prediction model usually used for fracture treatment design and optimization. The method is validated against published information of field productivity and production prediction by other complex methods. The method is then used to demonstrate that the accelerating effect is the only one source for the maximum of fracture conductivity, one of the major sources for the loss of fracture conductivity, and account for the source for discrepancy between the predicted and actual productivities. Finally, the implication of neglecting the accelerating effect in fracture treatment optimization is also investigated, emphasizing the need to incorporate this effect.
This work will be of importance to engineers in the predicted productivities, in particular for high pressure gas wells.

ARMA 15-0564

A new method for assessment of rock drillability based on indentation tests

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Abstract: The phenomena of low ROP (rate of penetration) due to the difficulty of making accurate evaluation of rock drillability is common during drilling in dense and hard formation in Tarim basin. The resistance of rock-crushing is a function of multiple variables, including the type of tool and rock mechanical properties. Therefore, the traditional methods based on one or several kinds of rock mechanical properties cannot truly reveal the resistance of rock breaking.
In this paper, experimental research on rock indentation fragmentation by single-indenter at varying confining pressure has been carried out with an indentation device controlled by a servo-hydraulic loading system. Moreover, measuring tool of high resolution three dimensional profile scanner has been applied to observe and analyze the shape and volume of crushing-crater. A new breakability index (BI) of rock considering the impact of both invasion difficulty of tool and rock brittleness is defined from force-penetration curves of indentation tests. The relationship of both specific energy (SE) and volume of crushing-crater (VC) with BI has been investigated, and the influence of confining pressure on the BI has also been studied.
The results indicate that both specific energy and volume of crushing crater have a good exponential relationship with breakability index. With increasing of the BI values, the VC values increase, while the SE values decrease. Besides, a good linear relationship between confining pressure and the BI is also found. With increasing of confining pressure, both the BI and VC values decrease, while the SE values increase. It can be concluded that the greater the BI values are, the more prone to breakage the rock is. Therefore, the proposed concept of BI could be used for assessment of rock drillability.
This work provides a new idea and method for quantitative evaluation of rock drillability.

ARMA 15-0610

Title: Attenuation of seismic waves in brine saturated Hawkesbury Sandstone: An experimental study

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The attenuation characteristic of compressional *(P)* and shear *(S)* waves in dry, water and different concentration of brine (10, 20 and 30% NaCl by weight) saturated Hawkesbury sandstone samples were measured in the laboratory at ultrasonic frequency range of 0.1-1.0MHz. The obtained results were analysed using pulse transmission technique and spectral ratios were used to calculate attenuation coefficient and quality factor (*Q*). The values were calculated relative to a reference sample (aluminium sample) with very low attenuation and the effect of salinity on attenuation characteristics of sandstone were evaluated. Velocity dispersion was observed for both *P* and *S* waves for all the tested conditions. It is observed that the attenuation coefficient is frequency dependent and linearly proportional to frequency both for *P* and *S* waves. Interestingly, with respect to dry value, the attenuation coefficient increases with the fluid saturation (both water and brine). Moreover, the calculated *Q* values reveal that the values are highly depended on saturation condition and the fluid saturation decreases the *Q* value compared to dry condition. Brine with different concentration of NaCl including 10, 20 and 30% were used to simulate the brine saturation effect and saturation was carried out in desiccators under vacuum for two months period. The sample saturated with 10% NaCl showed a similar behaviour to water saturated sample while 20 and 30% NaCl saturated samples displayed considerable variations in attenuation coefficient and quality factor. The attenuation coefficient decreases with increasing salinity of the pore fluid and consequently, increases the quality factor of the rock formation.
Keywords: Attenuation, quality factor, sandstone, compressional wave, shear wave

ARMA 15-0624

The use of multistage hydraulic fracture data to identify stress shadow effects

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Geomechanical modelling of stress changes during multi-stage hydraulic fracturing (MSHF) can help optimize the design of hydrocarbon extraction operations in unconventional low permeability low porosity reservoirs. Stress changes which occur during a single stage of MSHF have been known to affect subsequent fracturing stages. Issues such as increase in minimum horizontal stress, fracture re-orientation, restriction of fracture width and fracture growth, or termination of a fracture in a previously stimulated area, have all been modelled and shown to have an effect on hydraulic fracturing productivity. If an understanding and modeling capability of the effects of induced stress changes can be achieved, optimization of hydraulic fracture operations becomes feasible.

Given uncertainty and limited monitoring data, calibration and history matching with reservoir models are used to help design MSHF operations. Data from “similar” wells to those that will be later encountered are used to create a semi-empirical “model” that may have predictive value in design, but because the basis in physics of such models is weak, their predictive capabilities rapidly disappear if conditions are significantly different from those used to develop the empirical calibration factors.

This paper will examine the stress shadow effects during MSHF in unconventional reservoirs and the possibility of fracture spacing optimization. Both a complex mathematical model and a simple two dimensional model are introduced to compare efficiency and results. Recommendations are made concerning simplifying assumptions when it comes to MSHF and reservoir modelling in tight formations. History matched models are used to simulate geomechanical response during MSHF around several wells in the Montney Formation (Alberta). Stress shading is explored with parametric analysis in a finite element geomechanical model. The effects are quantified and calibrated. Recommendations will be made on the adjustment of stage spacing based on the extent and magnitude of the stress shadow effect.

ARMA 15-0645

The Impacts of Fracturing Fluid Viscosity and Injection Rate on the Near Wellbore Hydraulic Fracture Propagation in Cased Perforated Wellbores

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Hydraulic fracturing has been used as a major stimulation technique for oil and gas wells since 1947. Hydraulic fracturing is usually operated through the perforations in cased-hole wellbores. The presences of casing and cement sheath plus the perforation tunnels significantly complicate the mechanism of fracture initiation and near wellbore propagation in such wellbores.
In this study, hydraulic fracturing tests were conducted on 15 cm synthetically manufactured cubic mortar samples. The cased hole and perforations were created in the samples after casting and curing were completed. A true tri-axial stress cell was used to apply three independent stresses in order to simulate real far field stress conditions. In addition, dimensional analyses, which are known as scaling laws, were performed to provide a realistic correspondence between the results of lab experiments to field-scale operations. Three different fracturing fluids with viscosities ranging from 20 to 600 Kcp were used to investigate the effects of varying fracturing fluid viscosities and fluid injection rates on fracturing mechanism.
The results indicated that by increasing the fracturing fluid viscosity and fluid injection rates, the fracturing initiation and breakdown pressures increase and the fracture initiation angle also increases, which consequently results in more curved fracture planes. It was evident that fractures would reorient perpendicular to the minimum horizontal stress despite the angle of initiation. Furthermore, it was found that the presence of pressurized casing in the wellbore would rearrange the stress distribution around the casing in such a way that the created vertical fractures tended to deviate from the wellbore vicinity. This was more pronounced when more viscous fluids were injected at higher flow rates and consequently the fracturing pressure would increase and casing was further pressurized.

ARMA 15-0669

Caprock Safety Factor Assessment of SAGD Projects

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Abstract: Coupled reservoir-geomechanical simulations have become more and more popular when Steam-Assisted Gravity Drainage (SAGD) is employed for oil sand development. This paper presents a strategy in which two commercial simulators: CMG-STARS and FLAC2D are linked together and jointly executed for coupled thermal-hydro-mechanical simulation of multiphase flow, heat transfer and stress/deformation in porous formations when high pressure and high temperature steam is injected into oil sand reservoir. The simulation results are then used for caprock stability analysis and estimation of maximum sustainable injection pressure.
With the evolution of a steam chamber, temperature and pressure fields in the reservoir and caprock are raised, which could alter reservoir and caprock stress significantly to cause tensile and shear failure within and beyond the growing steam camber. The simulation models for STARS and FLAC2D are illustrated in Figure 1. Considering different wellpair spacing and injection pressures, 6 cases were analyzed in this paper. The pore pressure and temperature fields obtained from STARS is transferred to FLAC2D and a Mohr-Coulomb model is adopted for the geomechanical simulations.
Firstly, the safety factor against tensile failure at the base of the caprock can be computed and is shown in Figure 2. When the ratio of minimal total principal stress to fluid pressure is less than 1.25, it is assumed that tensile failure will happen in this cell. Secondly, a methodology that utilizes the simulations results to compute the factor of safety against shear failure along potential shear planes in the caprock was developed. The potential shear failure along any possible fractures is calculated using the conservative assumption that a potential failure plane could exist at any point with an

arbitrary orientation, as show in Figure 3. The factor of safety against shear failure along plane " *i* " is defined as the ratio of the area under the shear strength or resistance curve to the area under the applied shear stress curve, which is computed from the simulation results. Figure 4 schematically illustrates this concept. Utilizing a search routine to find the minimum factor of safety for all combinations of potential failure planes, a caprock integrity assessment can be conducted along with sensitivity studies on variations in material properties as shown in Figure 5. Figure 6 illustrates how wellpair spacing can influence the distribution of the shear failure factor of safety within the caprock. A discussion is also provided on the influence of caprock thickness on factor of safety calculations.
As the steam chambers develop within the reservoir, it is clear the factors of safety against both tensile and shear failure will decrease. Selection of material strength properties for the caprock is a critical factor in the defensible selection of an operating factor of safety at a given maximum steam injection pressure. The methodology presented in this paper can be used to rationalize shear failure factors of safety for caprock integrity and be used as a criterion for the control of steam injection pressure to prevent caprock failure and steam leakage.

Keywords: SAGD; Mohr Coulomb; oil sands; safety factor of caprock; caprock integrity; geomechanics; coupled simulation;

ARMA 15-0748
GLOBAL SENSITIVITY ANALYSIS OF GEOMECHANICAL FRACTURED RESERVOIR PARAMETERS

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Abstract
Unconventional petroleum reservoirs contain vast resources to supply the energy demand in the United States. However due to their ultra-low matrix permeability, the development of such reservoirs depends mainly on the ability to transport the underground fluid to the surface through extensive natural fracture networks subjected to geoemachanical deformation of the rock and fractures. Fluid injection and extraction operations are usually carried out in Naturally Fractured Reservoirs (NFR) as recovery process whose performance strongly depends on the flow properties of the fracture network and then controlled by geomechanical reservoir parameters, which are usually defined under uncertainty.
A important step for the design and control of injection and production operations in those reservoirs is to find the relative contributions of the geomechanical parameters (e.g., material properties and far-field stresses) in the variability of given performance measures (e.g., bottomhole pressure), considering a large-scale reservoir. Previously reported works using coupled geomechanics/fluid-flow numerical simulators of NFRs have been limited to local sensitivity analyses because a global sensitivity analysis may require hundreds or even thousands of computationally expensive evaluations of large-scale numerical simulations. To overcome this issue, the Fast Multipole-Displacement Discontinuity Method (FM-DDM) is suggested. The FM-DDM solves for the simultaneous changes of normal and shear displacement discontinuities and fluid pressure inside the fractures. To reduce the computational complexity for large-scale situations, the FM-DDM accelerates the matrix–vector products (Ax) in iterative algorithms without forming the coefficient matrix (A) explicitly reducing then the execution time and saving memory.
This paper presents an efficient global sensitivity approach based on the Analysis of Variance (ANOVA) and the FM-DDM to assess the uncertainty of geomechanical reservoir parameters. The proposed approach was evaluated in the context of the global sensitivity analysis in a large-scale NFR subjected to injection and production operations. The geomechanical parameters were selected as the rock mechanical properties (shear modulus, Poisson ratio, shear and normal joint stiffness), and far-field stresses, and the performance measures were chosen as fluid pressures in the injector and producer wells. The results show the effectiveness and efficiency of the proposed approach since it allows establishing the relative contribution associated with the uncertainty of the geomechanical properties (main factors and interactions) in the variability of well performance metrics using a

limited number of computationally expensive geomechanics/fluid-flow numerical reservoir simulations.

Keywords: Global sensitivity analysis; ANOVA; Geomechanical parameters; Naturally Fractured Reservoirs; Fast Multipole-Displacement Discontinuity Method (FM-DDM).

ARMA 15-0534

Application of Programmatic Gridding Technique to Advanced Reservoir Geomechanics Modeling

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Reservoir Geomechanics as a reckoned role incorporates with not only performances of reservoir flows but its leakage-proof security. In order to take near and far-field Geomechanics into account during modelling CO_2 injection process into deep saline aquifer, it is studied how to sufficiently control a compatible numerical discretization between reservoir flow and reservoir Geomechanics. Application of gridding technique is implemented through source code programming. It is introduced self- developed realization in commercial software package from unstructured meshes for the sake of efficiently extending overlying strata up to ground surface, to a regularly refined focus capable of stepwise capturing CO_2 plume, surrounding by circumference divided into cells gradually scaling up along radiant directions. The resultant distributions of ground surface deformation simulated using different gridding algorithms are compared and some principles counter-intuitive to a usual work flow in analyzing ground surface heave induced by deep gas injection are studied. In addition, as a foundation to facilitate the decoupling strategy, an tractable interface is programmed to provide completely identical models as well as their discretization between reservoir flow simulation software CMG's GEM and reservoir Geomechanics modelling package Itasca's FLAC-3D.

INT-P-01:

Monday, June 29, 2015, 03:30 pm - 04:30 pm

ARMA 15-0647

NUMERICAL STUDY OF ROCK AGGREGATE MATERIALS UNDER VARIOUS LOADINGS

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Abstract: Cemented and uncemented rock aggregate materials form the main part of pavement layers play a significant role in withstanding vehicle-induced cyclic loading. However, increased traffic loadings undoubtedly cause fatigue-cracking and particle breakage, which leads to continued settling and pavement failure. In this paper, Particle Flow Code (PFC), which is employed with Discrete Element Method (DEM), is used to investigate the behavior of rock aggregates under various loading conditions. In the first simulation series, the rock aggregates of five different shapes and four different sizes, assembled at a certain volume ratio, were subjected to compression tests under fixed lateral wall and constant confining pressure. Following results were obtained: 1) Cracks initiated more easily in larger particles and in the angular rocks at sharper corners; 2) More shear cracks occurred than the tensile cracks; and 3) More microfractures were obtained with the increasing confining pressure (Figure 1). In the second simulation series, a Cement Treated Base (CTB) layer reconstructed by real cemented aggregate material together with simplified asphalt layer and subgrade layer was incorporated into a flexible pavement (Figure 2). The same cyclic loading used for the first simulation series with specified amplitude and frequency values were applied on this second set up. The results showed : 1) Settlement of the layers increased significantly with increasing stress amplitude; and 2) Settlement of the layers were found increased with increasing loading frequency while decreased with the incresearing of binder content of CTB. Some

experiments are currently in progress to compare between numerical and experimental results. This research will provide a further understanding of the damage of cemented and uncemented granular materials and a good guidance for the selection of road materials and pavement construction.

Keywords: Rock aggregate, Crack propagation, Numerical simulation, Pavement, Discrete element method, CTB

ARMA 15-0784

Application examples of a new optical fiber sensor for reading RGB intensities of light returning from an observation point in geo-materials under various natural conditions

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Two plastic optical fibers, both having diameter of 1mm, are used to read local disturbance or deformation at a point in granular material, such as sand, soil, or broken rocks. As light is sent into the 1st fiber and reaches its end, it leaves the fiber and hits surfaces of nearby particles. Part of the reflected light then gets into the 2nd fiber, which can be digitally measured by using photo diode. Two fibers can also be aligned such that a gap is created between the fibers for sensing.
The paper describes results of several laboratory and field experiments using these new fiber sensors. The examples include cases in which fiber sensors were used to interpret seepage, sand mass movement, liquefaction, passage of boundary plane between two different types of liquid in soil, turbidity, sand sedimentation in sea and so on. These results show that the proposed new sensors will be able to support data acquisition procedures in many different engineering projects.

ARMA 15-0212

A Practical Log-Based Approach for Assessing and Preventing Wellbore Instability Considering both Mechanical and Shale Swelling Effects

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Although various techniques and drilling practices have been developed to remedy drilling problems as a result of shale swelling, a quantitative estimation of shale swelling potential has been difficult to establish in the oilfield. The cation exchange capacity is one parameter that has been shown to control the swelling of shales both qualitatively and quantitatively. A correlation derived from basic physical principles for the cation exchange capacity (CEC) of shale formations using common log data of temperature, resistivity, and sonic slowness has been modified using available core and cuttings test data. CEC is then used to distinguish problematic, smectite-rich shale formations from the trouble-free, illite-rich formations using a threshold value. An empirical relationship that involves calculated values of CEC and thresholds is then developed to estimate the osmotic pressure resulting from an imbalance of water activities—in effect, estimating a higher mud weight needed to stabilize the well. This methodology was applied to a well drilled in the North Sea combined with mechanical wellbore stability analysis and shows good agreement with wellbore enlargement and well events. This technique has multi-fold benefits, identifying problematic drilling intervals owing to an abundance of smectite, estimating a minimum mud weight necessary to prevent drilling problems as a result of shale swelling and ultimately determining whether a well is drillable with a water-based mud system.

ARMA 15-0521

The Effect of Rock Mineralogic and Petrographic Properties on Stone Cutting Feed Rate

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The feed rate of the natural building stone cutting processes is determined by the properties of the natural stone and the machine being used. The most significant factors that affect the feed rate during natural building stone cutting processes are the mineralogic and petrographic properties of the natural stone. The feed rate is determined by the operator, and is generally selected based on the operator's own experience. Regardless of the type of stone being cut, the main goal of natural building stone cutting processes is to achieve an optimum feed rate, while also ensuring minimal power expenditure and tool wear. In this study, the cutting data for nine different natural building stone cutting processes classified under three different groups were investigated. The mineralogic and petrographic properties were determined for the natural stones being cut, and the effects of rock mineralogy on the optimum feed rate was evaluated based on the comparison of feed rates with these properties. In this context, the cutting processes of building stones consisting of marble, limestone, and travertine were evaluated. According to the study data, factors that played an important role in the selection of feed rate under industrial cutting conditions include the mineral structure of the rock, the mineral grain size, the porous structure of the rock, rock hardness, and the layer structure. Natural building stone cutting processes can generally be classified into three groups as low-speed, medium-speed, and high-speed cutting conditions. In each one of these groups, the cutting speeds are directly affected by the mineralogic and petrographic properties of the rock.

Natural building stones;Rock cutting; Feed rate; Rock properties.

CIV-P-01:

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ARMA 15-0043

Structural design of tunnel supports by combining a point estimate method with a deterministic numerical analysis code (FLAC2D)

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The objective of this study is to propose an alternative way for the probabilistic structural design of tunnel supports in combination with a deterministic numerical analysis code, FLAC2D which has been popularly used in numerical simulations of underground structures. To achieve this, we proposed an approach for linking a point estimate method, which is one of the probabilistic methods for reliability assessment, to the FLAC2D solver and developed a software program, called TunnelRA (Tunnel Reliability Assessment), which facilitates the probabilistic reliability assessment of tunnel supports considering the uncertainties in the properties of ground and supporting materials. The TunnelRA program controls all processes associated with numerical calculations performed by FLAC2D and consequent probabilistic analyses, and writes out probabilistic results to files in ASCII format for a graphical plotting. To investigate the validity of the present probabilistic approach, the developed program was applied to a lined-circular tunnel problem with a closed-form analytical solution. We compared the calculations between the present approach and a Monte Carlo simulation of the analytical solution, which can be regarded as an exact method. The validity of the present approach was demonstrated in the accurate estimation of the statistical moments of the performance functions related to the lined-tunnel. In addition, we applied the present approach to the structural design of a steel liner which is installed in a pressurized tunnel used for storing compressed natural gas at a maximum pressure of 15 MPa. In this application, we investigated the probability of failure for the steel liner by varying the liner's strength and thickness and provided information for decision making in structural design. The results of the present work demonstrated that the numerical approach in this study could be used for designing tunnel supports and for making relevant decisions in a quantitative manner.

ARMA 15-0146

Geo-mechanical model test for Global Stability of High Arch Dam and its Engineering Applications

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Abstract: A large number of world-class high arch dams are currently under construction or will soon be built on the large rivers in West China. These large dam projects are usually located in high mountains and deep valleys with complex geological conditions. The global stability and safety of dam and foundation is a major concern. Geomechanical model test is one of the main methods to study and solve this problem. Three test methods of geomechanical model are presented in this paper. The overloading method is used to test the overload capability by exceeding the upstream water pressure. The strength reserve method considers the mechanical parameter reduction of weak structural planes and it is used to study the reserve capability. The comprehensive method combines overloading and strength reduction and it is conducted to comprehensively evaluate the global stability of project. According to the rupture test principle and model similarity theory, the evaluation system on global safety factors by three kinds of model test is established, and the testing technique based on the temperature-dependent similar material for simulating the strength reduction is also proposed. These basic studies offered the theory and technical supports for dam model test. Finally, the 3D geomechanical model tests were applied to Xiaowan arch dam (294.5m high) and Dagangshan arch dam (210m high) to study the global stability, failure mechanism and process. These research results have been applied in practical project and provide an important scientific basis for the evaluation of stability, safety and reinforcement effect.

Key words: 3D geomechanical model; comprehensive method test; global stability safety factors; temperature-dependent similar material; engineering applications

ARMA 15-0685

Evaluation of conditions of rock bolts affected by corrosion using pulse echo and acoustic emission methods

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The construction of civil or mining structures usually requires the installation of bolts and anchors (rock bolts) to strengthen, consolidate and stabilize the rock-rock, rock-concrete or concrete-concrete interfaces. It's frequent that rock bolts are installed in highly acidic or highly alkaline environments.

In this paper, we present a case where visual inspection of a large field structure reported that the majority of rock bolts exhibited advanced signs of corrosion at the locking nut and on the support plate. An experimental study was put on to validate the non-destructive methods aiming at detecting the state of corrosion in these rock bolts in real conditions.

The acoustic techniques using the waveguide principle were applied on rock bolts of 25.4 mm in diameter which were embedded into concrete blocks (300*300*800 mm) and submitted to accelerated corrosion using the impressed current corrosion method. Pulse echo (PE) measurements were taken every 24 hours. In addition, an acoustic emission system (EA) was attached to the corroded blocks as well as a control block, in order to monitor the corrosion activity during the corrosion process. Half-cell potential was performed at the beginning and in the end of the corrosion process. A quantitative assessment of the energy of the first back wall echo that comes from the end of the rock bolt and the back wall trailing due to the mode conversion shows that poor bonding between the bolt-grout interfaces due to corrosion yields low energy. It was observed that a good bonding show at least twice the energy of the echo and the maximum energy was observed on a free anchor bar. Finally, the tests were conducted in an underground power house for detection the

rate of corrosion of the installed prestress roc bolts. This paper shows that, PE tests can be used as an effective measurement for corrosion detection in rock bolt.

Keywords: Rock bolt; corrosion, ultrasonic pulse-echo; corrosion; non-destructive testing; guided wave.

ARMA 15-0223

Modeling Natural Fracture Network Using Object-Based Simulation

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Object-based model has demonstrated a great potential to stochastically realize natural fracture networks. This model is based on "Random Disk" model and is constructed by spatial interactions of objects located at random points in the reservoir domain. In this model, marked point processes are implemented to honor an assumed fracture characteristics' distribution where the fractures are two-dimensional zero-thickness circular disks with a random distribution generated by Monte Carlo sampling. This sampling assumes that the fracture radius, orientation, and location are not correlated to each other. Based on geological observations, a Poisson-point process in Rn can successfully realize fracture spacing by an exponential distribution.

The current work implements the object-based method with the above characteristics for a natural fracture distribution. Fractures are divided into two groups based on their alignment which is acquired by Monte Carlo sampling from two Gaussian distributions with 90-degree shift in the mean value; this hypothesis is validated considering the frequently observed checker-board fracture patterns in the outcrops. The growth of the fractures in the second group or the secondary (daughter) fractures can be terminated by a criterion derived from the distribution of the fractures in the first group or the primary (parent) fractures. For data assimilation purposes, a smooth seismic distribution for fracture density is mimicked by simple krigging which inherently possesses a smoothing nature. Then, the generated seismic data is honored by revising the fracture distribution such that in areas with less fracture density we have fewer fractures.

This work provides a novel, yet easy and fast workflow to stochastically model a natural fracture network following the attributes offered by seismic data and concludes an orthogonal or bidirectional fracture pattern. This pattern can be easily extended for multi-directional fracture patterns using the proposed framework.

ARMA 15-0593

Elastoplastic solutions to deep-buried circular tunnels in transversely isotropic rock masses considering intermediate principal stress

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The influence of intermediate principal stress is usually ignored for the problem of a deep-buried circular traffic tunnel under plane strain condition. But the deformation of surrounding rocks in plastic area has greater error. A number of layered rock masses occur in geotechnical and underground engineering and they are often treated as the transversely isotropic solid materials. To consider the influence of the intermediate principal stress on deep-buried circular tunnels, plane strain hypothesis is given and the new Drucker-Prager criterion compatible with the transversely isotropic materials is obtained. Then Mohr-Coulomb criterion is precisely matched to the new Drucker-Prager criterion. The analytical expression of the intermediate principal stress in plastic state for the transversely isotropic perfect elastoplastic materials with dilatancy is deduced based on the criterion. According to the expression of the intermediate principal stress, the analytical expressions of the displacement and stress in plastic area for a deep-buried circular tunnel in transversely isotropic rock masses can be obtained. A practical engineering case is given and the regularities that transversely isotropic parameters and dilation angle act on the displacements in the plastic area of the deep-buried circular highway tunnel in transversely rock masses are discussed. So,

the elastoplastic solutions may provide a more reasonable theoretic basis for the calculation and design of the deep-buried circular traffic tunnels.

ARMA 15-0462

Experimental study on loading-unloading failure process of marble in Jinping II hydropower station, China

Peng-Zhi Pan[1], Wei-Wei Ji[1], Xia-Ting Feng[1]

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In this paper, several experiments under different loading-unloading paths are carried out to investigate the failure mechanism of deep-seated marble in Jinping II hydropower station, China. The experiments include pseudo-triaxial compression test, confining pressure reduction test with constant σ_1 and confining pressure reduction test with variable σ_1. From the experiments, we got crack volume strain and volume strain (Fig.1), which are used to analyze the failure process of the marble. The change of crack volume strain and volume strain indicates the different stage of the marble failure. It is found that, the marble failure process is divided into 6 stages including initial crack compaction, elastic stage, damage development, macro-crack development, rock structure stage and residual strength stage. During the initial crack compaction stage, different confining pressures produce different compaction extents of initial crack which indicates the relation between the confining pressure and the compaction extent of initial crack. Besides, the influence of confining reduction is mainly discussed. The comparison is made between confining pressure reduction test controlled by axial stress with constant σ_1 and confining pressure reduction test controlled by axial strain with variable σ_1. The Griffith locus is used to explain the different post-peak behaviors induced by those two control methods. It is found that the inflection point of volume strain of Jinping II marble always lags behind the unloading point and the macro failure happens at 80%-95% of peak stress. This behavior plays an important role to control the support time when tunnels are excavated and helps us to understand rock failure process as well as provides a theoretical basis for preventing the failure of hard rock under loading-unloading path.

Keyword: rock mechanics; failure process; deep-seated marble; confining pressure; loading-unloading experiment

MIN-P-01:

Monday, June 29, 2015, 03:30 pm - 04:30 pm

ARMA 15-0477

Ground subsidence model for a panel caving exploitation at El Teniente mine - CODELCO CHILE

Alejandro Espinosa[1]

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The generation of a subsidence crater on the surface derived from an underground mine exploitation, has been under study since the 70's with works done by Peck (1969), Shandbolt (1978), Kvapil et al (1989) and Flores (2005), among the most famous. All these studies were developed using available observations together with the characterization of rock massifs and materials disposition, to elaborate rules that would allow the estimation of the extension of motion caused by the phenomena of subsidence.

Since 2010, El Teniente mine of CODELCO – CHILE has been monitoring the ground subsidence generated by the underground exploitation using radar satellite data (InSAR) and the application of methods based in differential interferometry (DInSAR). This has allowed obtaining accurate ground motion measurements over large extensions of land, which have been used to develop a behavior model that establishes a link cause-effect between the underground works and the surface subsidence. This conceptual model establish a consistent relationship between underneath mining drawing and subsidence evidence over surface.

These analyses have been applied in the delineation of the subsidence effect and in the development of a conceptual model for the subsidence process that is generated by the phenomena from the base of the exploitation up to the surface. The results indicate a significant difference between traditional estimation of subsidence angles and results obtained from INSAR technology. Finally, the subsidence interpretation using interfereometric satellital methodologies show a reduction of extension effect over surface due to underground drawing with a consequent reduction in angles of breaking and influence.

<u>ARMA 15-0817</u>

Analysis and Design of Pillars for Cave Mining Developments - A Comparative Assessment of Empirical Methodologies

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The stability of mine drifts exploited by gravitational caving methods depends not only of geological characteristics and in-situ stress state, but also of mine design, that includes the drift width and orientation, height of columns (geometrical factors), extraction rate, time of mine activities, and caving rates (Brown, 2003). In these exploitation methods the change of stress state associated to the undercutting induce a great damage in the drifts.

Usually the study of the strength and stability of pillars in block cave mining is performed through empirical, analytical and numerical modeling methods. The most used are the empirical methods that relate the UCS of intact rock, the rock quality and size of the column. There are a variety of formulations that provide different results for the same design. Most of the proposed formulas have been analyzed with databases bounded to a single mine, so that might present a biased rock type, form the pillars or for one stress state. Additionally, the formula used must be able to scale the UCS of a laboratory test to the scale of a real pillar (Yrarrazaval, 2013).

Pillar stability is critical at both the undercut and production levels for the successful operation of block cave mining. The stability of pillars in block cave mining is affected by both the excavation method and the size of the openings they support (Bharani et al., 2010).

Geomechanical engineers typically use rock mass classification approaches to estimate rock mass strength. These approaches are based upon experience gained at relatively shallow depths (typically <1000 m) and from observations near excavation walls. Therefore, the application of these standard approaches, to rock masses at greater depths and for estimating the strength in pillar cores, could be flawed and lead to costly mistakes (Kaiser et al., 2010).

Methods of Hoek-Brown (1997), Stacey-Page (1986) and Lunder-Pakalnis (1997), permit assess the strength and stability of the pillars in different scenarios of vertical stresses (identifying pre-mining and transition zones), doubling and tripling the pre-mining stresses, the order of the intact rock UCS, which represents the case of abnormally loaded pillars. Safety factors of the pillars calculated for the different scenarios are highly variable, being in some cases greater than 3.0 and less than 1.0 in others, which leads to great uncertainty in defining the geometry of the pillars.

This article develops a comparative study of different methods exist to analyze the strength and stability of the pillars of an underground mine by caving as the undercut phase is performed. In addition, the main objective of this work is to contribute to a better design of pillars, essentially regarding the application of traditional

ARMA 15-0850

Movement Regularities of Roof Strata in Extra Thick Coal Seams with Fully-mechanized Mining

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This paper was prepared fro presentation at the 49th US Rock Mechanics / Geomechanics Symposium held in San Francisco, CA, USA, June 28 – July 1, 2015.

ABSTRACT: Strata behaviours in some extra thick coal seams with fully-mechanized mining are fierce. In some circumstances, some hydraulic supports were still crushed even though their working resistance had been sharply increased beforehand comparing normal supports in medium-thick coal seams. Based on a field measurement, numerical simulation, laboratory simulation experiments and theoretical analysis, the movement regularities of roof strata in extra thick coal seams with fully-mechanized mining was studied in this article. The studies shows that: if an extra thick coal seam is mined on a single time, the thicker the coal seam is, the bigger is the vertical and horizontal movement range of the surrounding rocks, and scope and peak value of the abutment pressure increases obviously. The concepts of “immediate roof” and “basic roof” in extra thick coal seam are different from those in medium-thickness coal seams. The rock strata above the extra thick coal seam would form a structure like “inverted-step cantilever group-articulatedrock beams”. Such structure breaks periodically with the advancing of the working face, where roof weighting comes regularly in “small cycle – big cycle”. Different from high cut mining (3.5`7.2 m. mining height), physical and mechanical features of the top coal in top coal caving mining (≥7.2 m. height) play a key role in strata behavior. Underroof deformation pressure, the top coal was condensed to “a rigid coal structure”. Some roof strata deform the top coal while exerting no pressure on the hydraulic supports and they are called “strata without deforming pressure”. While the other part above such strata is called “strata with deforming pressure” since it exerts deforming pressure to hydraulic supports via “rigid coal structure”. Based on the above knowledge, the lower limit of working resistance of hydraulic support in high cut mining and top coal caving for extra thick coal seams are proposed.

ARMA 15-0851

Modeling Overburden Strata Movement in shallow coal seam Longwall Mining

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In many regions of China, there were lots of small coal mines using blasting mining or roadway mining to excavate the coal resources. Due to the outdated mining technology in small coal mines, the resource recovery rate is only 10% to 25% with lots of abandoned gateroads and gobs. The damage area caused by the small coal mines mining amounted to nearly one hundred square

kilometers. Nowadays, when the longwall panels lay out in these areas, there are many mining difficulties such as pillars left and unpredictable small gobs. Therefore, reasonable recovery mining technology must be taken to reclaim the wasted resource in disturbed coal areas. In this paper, protem EM-47 TEM instrument was used to detect the exact location of the old gobs caused by excavating the small panels in Cui Jiazhai Coal Mine in the northwest of China. On the basis of the detection, three-dimensional geological model of destruction was established. By using FLAC-3D numerical simulation software, the stress distribution was simulated when the panel face passed through the disturbed areas. The reasonable angle of the panel face was analyzed when the panel face passed through the abandoned gateroads. The results show that, in the process of panel face passed through the abandoned gateroads, the angle of the panel face was adjusted to 7°-10°, the headgate should be 20m advanced than the tailgate. The abandoned gateroads on both sides of coal pillars have not damaged at the same time, no large-area pressure concentration was happened above the main roof. Therefore, the coal resources of disturbed areas can be successfully recovered by using underground longwall mining.

Keywords: small coal mine mining, disturbed areas, abandoned gateroads, angle of the panel face, numerical simulation

ARMA 15-0567
Using particle flow code in unloading of sliding mass

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For keeping mine alive and extracting minerals while a giant sliding mass exists in open-pit mine and it is flowing on the benches and minerals like debris, at this time, it is necessary to unload the sliding mass and debris. For achieving this aim, monitoring should be done along with unloading of sliding mass so that displacement and velocity values of sliding mass do not exceed a certain limit and do not cause a serious incident. One of the suitable software which is able to model and unload this sliding mass, is PFC (Particle Flow Code) and it is based on Discrete Element Method. Because of this, in this paper sliding mass has been modeled as a sample in an open-pit mine and unloading it in seven stages has been done. During the unloading of sliding mass, maximum velocity and displacement among the particles have been obtained. Also, Angooran mine, which is the largest metal mines in Iran and also one of the most economical lead and zinc mines in the world, has been studied in this article. Sliding mass volume, which occurred in Angooran mine, was about 12 million m^3, i.e. 25 million tons. The sliding mass moved about 100 m horizontally and 45 m vertically.
Keywords: particle flow code; Unloading; Displacement; Velocity

ARMA 15-0235
Nonlinear Failure Mechanism and Dynamic Simulation of the Deep Rock Engineering

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Due to the high geo-stress state of the surrounding rock mass in deep rock engineering, which attends to induce large deformation, rock burst, zonal disintegration and other disasters, the traditional theories of statics continuum rock mechanics cannot explain many problems in the deep tunnel sufficiently. This article presents a new dynamic constitutive model from the material point of view of dynamic failure, according to the release, dissipation and transfer of energy under the unloading of deep rock mass, in which process the volume deformation experience elastic resilience and volumetric dilatation, and the shearing deformation may experience pre-peak (elastic and internal frictional hardening stages) and post-peak (softening and residual failure stages) stages. And

this model also describes the elastic resilience and volumetric dilatation with time is considered to establish the volume deformation constitutive relationship; The enforce process of strength is described, and three Coaxial conical surfaces (yield surface peak strength surface and residual strength surface) are used to present this evolution. In this model, according physical meso-mechanics, fracture lag time, which present the contribution of different structural level, is employed to establish the rheological equation for hardening stages; According crack movement spreading theory, fracture time, which present the propagation and link up of macro crack, is employed to establish the equation of strength evolution, finally deformation constitutive equation is given using theory of plastic flow. With this model the article also studies on the deformation in deep rock mass by the numerical simulation of the Diversion Tunnel of Zhuji coal mining.

ARMA 15-0224

Underground Disposal of Fine Coal Waste

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[1]Southern Illinois University Carbondale, [2]Southern Illinois University Edwardsville, [3]University of North Dakota

The use of slurry impoundments has traditionally been the primary method of disposal of fine waste slurry resulting from the recovery of fine coal from coal preparation plants. However, disposal of coal waste has become challenging with stringent regulations for surface disposal facilities. Underground coal mines with about 50% extraction ratio would be attractive storage space to dispose some of the coal waste products. The process of backfilling of mine void space is called slurry backfilling. This method would eliminate environmental, health, and safety risks associated with the surface disposal facilities such as impoundment failure due to ground motion, subsidence, crack development, etc. Although slurry backfilling have significant advantages, it may raise some mine stability concerns. As the floor or pillars of the mine exposed to moisture, they may soften and loose strength. The softening may result in failure of the mine and vertical deformation propagation to the ground surface. In this study, the slurry backfilling effect on stability of a couple of Illinois mines is investigated. These mines are using slurry backfilling in their worked out zones. The mine floor consist of non-durable claystone material with various thicknesses. The geotechnical and geological information of the mine roof, pillar, and floor will be analyzed. The stability of these mines will be evaluated using empirical and numerical methods considering the saturation of floor beds and pillars with slurry. This study will help mining companies to identify the subsidence risks associated with slurry backfilling and also if this practice has to be modified to eliminate the potential risks.

Keywords: Waste disposal, mine stability, softening, slurry backfilling

Technical Session 13 – California West
Coupled Process Modeling in Petroleum

Monday, June 29, 2015, 04:30 pm - 06:00 pm

Chairs: Dale Walters & David Yale

ARMA 15-0814

Multi-scale X-FEM Faults Simulations for Reservoir-Geomechanical Models

Jean H Prevost[1], N. Sukumar[2]

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Faults are geological entities with thicknesses several orders of magnitude smaller than the grid blocks used to discretize reservoir and/or over-under-burden geological formations. Introducing faults in a complex Reservoir and/or Geomechanical mesh therefore poses great meshing difficulties. In our work, we introduce faults in the mesh without meshing them explicitly, by using the extended finite element method (X-FEM) in which the nodes whose support intersects the fault are enriched. For the Geomechanics the fault is treated as an internal displacement discontinuity which allows slipping to occur using a Mohr-Coulomb type criterion. For the Reservoir the fault is an internal fluid flow conduit which allows fluid flow in the fault as well as to enter/leave the fault. In the X-FEM, the framework of partition of unity is used to enrich the nodes. The faults are represented by enriching the displacement approximation with a discontinuous (Heaviside) function, whereas the approximation for the fluid pressure includes functions that admit a discontinuity in their normal derivative across the fault. The procedure has been implemented in both 2D and 3D for both structured and unstructured meshes. Examples that demonstrate the versatility and accuracy of the procedure(s) will be presented. Also, the influence of rate of loading on activation of faults will be demonstrated.

ARMA 15-0411

Observation and Modeling of Fluid Flow under Matrix and Fracturing Injections in Unconsolidated Sand

Alexander Chudnovsky[1], Yuri Shulkin[1], Edward Golovin[1], John Dudley[2], George Wong[3]

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Recently conducted small (laboratory) scale experiments with fluid injection in unconsolidated sand packs revealed various patterns of fluid flow. Some of these patterns depart from that commonly discussed in literature. The experiments have been conducted in a pressure chamber under true-triaxial confining stresses with two types of sand packs: (a) homogeneous and isotropic; and (b) a layered, transverse-isotropic sand pack with fluid injection into a thin sand layer between two impermeable confining layers. The confined sand packs are approximately a 60cm cube, with a 1cm vertical borehole through the center. Tests included a series of about one liter fluid injections at various injection rates using a variety of fluid compositions. Tests were designed to investigate how fluid injections below and above the minimum confining stress affect the flow behavior in the sand pack and injectivity.

Under matrix injection conditions (i.e., injection pressure below minimum confining stress), the initial sand pack structure is practically undisturbed. Thus, matrix injection in homogeneous as well as in layered sand packs results in a homogeneous and axisymmetric fluid flow distribution. Under fracture injection conditions using a clear low viscosity fluid (i.e., injection pressure above the minimum confining stress), a heterogeneous and/or anisotropic fluid flow pattern is observed in both types of sand pack. Heterogeneous fluid flow in such cases is associated with the formation a large scale perturbations of the initially homogeneous sand packing in the sand pack regions adjacent to the wellbore. Under fracture injection conditions using a solids-laden fluid, a very different fluid flow pattern results. Specifically, highly localized fluid flow pattern through narrow crack-like openings is created in the sand pack, where the ‘cracks’ have a clear filter cake on their surface.

This paper briefly reports various test conditions and their corresponding fluid flow patterns, discusses the underlying physics, and outlines a mathematical model of the observed fluid flow through unconsolidated sand under matrix and fracturing conditions.
Keywords: flow pattern, injectivity, confining stresses, matrix injection, fracturing injection, unconsolidated sand.

ARMA 15-0763
Simulation of a Microseismic Depletion Delineation Test
Jack Norbeck[1], Roland Horne[1]
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In many reservoir engineering applications, it is important to incorporate a realistic description of the geologic structure of the reservoir into conceptual models and numerical models in order to establish appropriate interpretations of reservoir behavior. Several examples include hydraulic fracture treatment design, interpretation of microseismic monitoring data, and development of response strategies related to induced and triggered seismicity at wastewater disposal sites. In each of these cases, the interaction between fluid flow and the geomechanical response of fractured and faulted rock will have a direct influence on the reservoir behavior, and therefore also on the engineering decisions that must be made.

In this paper, a novel numerical modeling framework is introduced that is able to efficiently simulate the coupled physical processes of fluid flow, heat flow, and mechanical deformation of fractures, faults, and surrounding matrix rock. The technique is able to incorporate an explicit representation of the geologic structure of the reservoir by using an embedded fracture modeling strategy, which provides significant advantages over more traditional discrete fracture modeling approaches. Mechanical deformation of fractures and faults and the associated discontinuous displacement fields that arise are treated rigorously. Detailed models of friction evolution along fracture and fault surfaces are included to model seismicity. Fracture propagation can occur. In addition, poroelastic and thermoelastic stresses that are generated due to pressure and temperature gradients in the reservoir are considered in the model.

The present work extended a reservoir model called CFRAC. The calculation of mass and heat transfer in the fractures and surrounding rock was performed using an embedded fracture modeling approach. Embedded fracture techniques allow for a nonconforming numerical discretization, which is the critical component in the model that permits an arbitrarily complex description of geologic structure and for straightforward treatment of fracture propagation. Poroelastic and thermoelastic deformations were calculated using a standard finite element method. The poroelastic and thermal stresses were then resolved onto fracture surfaces, and used as additional traction boundary conditions in the displacement discontinuity method that was used to calculate fracture deformation. The coupling between these various physical processes was performed in a fully-coupled, sequential implicit scheme.

The model has direct relevance to practical-based and research-based applications in injection-triggered seismicity, unconventional hydrocarbon reservoir stimulation, geothermal reservoir stimulation, and heat recovery from geothermal reservoirs. As an example of the utility of the model, a numerical experiment related to triggered seismicity in a wastewater disposal setting was performed. The influence of poroelastic and thermoelastic stresses on post shut-in seismicity was investigated.

ARMA 15-0607

The fully coupled fluid flow and Geo-Mechanics model for simulating simultaneous multiple hydraulic fractures propagation in horizontal wells.

Xin Chang[1], Xian Shi[1], Yuanfang Cheng[1], Xiuting Han[1]
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The multistage hydraulic fracturing technique from horizontal wells is widely used for the production boost in shale gas/oil formations. But, some critical problems need to be addressed about the "stress shadowing" problems in tightly-spaced hydraulic fractures at a given fracturing stage since not all the fractures are sufficient. A fluid-mechanical coupled hydraulic fracture model from a horizontal wellbore for simulating multiple transverse fracture propagation by finite-element method is presented and a novel triangular gird split method (TMSM) is used to handle the complex stress filed of fracture tips. The fracture curved direction and propagation path are determined using linear elastic fracture mechanics. Specially, this hydraulic fracture model fully accounts for the stress interaction between adjacent fractures, and the fluid flow pressure drop along wellbore and perforation clusters frictions are also considered through empirical equation. Thus, the flow rate entering a given fracture can be exactly computed by the single rank inverse Broyden iterative method. We present a case study investigating the effect of in-situ stress anisotropy, pump rate, perforation density and Young's modulus etc. on the stress interference. Our results demonstrate the outer fractures prefer to grow at deviation angle and inner fractures propagation can be restricted severely. Moreover, the larger the perforation density and the smaller the cluster spacing, the more obvious stress interference can be observed. The pump rate, the differential stress and the Young's modulus are the most important parameters controlling the stress shadowing severity and size. One can use the simulation results for sensitivity analysis of reservoir properties and fracture treatment parameters for shale gas/oil stimulation design. Furthermore, this conclusion can better understand the fracture network physical mechanisms while the combination of this model and reservoir-simulation model can be extended to production prediction and analysis.

ARMA 15-0147

Stress Dependency of Rock Tensile Strength

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Hydraulic fracturing is crucial to geothermal and hydrocarbon recovery. The rock tensile strength is overcome using a pressurized fluid during the initiation of a fracture. Tensile strength has historically been assumed to be a stress independent property of rock depending solely on the rock type. Previous studies on igneous rocks suggest otherwise. Our experiments on Berea and Tennessee sandstone show a dependency of tensile strength on the confining stress. Mineralogy, porosity, permeability, acoustic velocity, mercury capillary pressure and grain size were measured to characterize these rocks. Confined Brazilian tests were carried out to observe the tensile fracture initiation and propagation under confined stress conditions. Strain gauges recorded the deformation leading to and during failure. The measurements show a strong dependency of tensile strength on confining pressure; however, tests were limited to a maximum confining pressure of 1000 psi. As the strain data indicate, confining pressure hinders the microcrack growth and nucleation. Tennessee sandstone which has a higher tensile strength at atmospheric pressure than Berea sandstone shows slightly greater increased tensile strength with confining pressure.

ARMA 15-0244

The effect of poroelastic stress changes on the triggering front of induced seismicity during fluid injection

Roman Rahner[1], Hiroki Sone[1], Georg Dresen[1]

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The effect of poroelastic stress changes on the occurrence of injection-induced seismicity has recently been recognized as an important additional mechanism to pore pressure diffusion. Previous theoretical and numerical studies indicate that injection induced stresses have a stabilizing or destabilizing effect depending on relative position with respect to injection point and principal stress directions prior to injection (Altmann et al. 2010, 2014, Schoenball et al. 2009). Therefore, in addition to the migrating pore pressure front, induced stresses have the potential to influence the triggering of seismic events. Consequently the shape of seismic event clouds is affected by pore pressure diffusion and induced stresses.

In this contribution, we analyze in detail the spatio-temporal changes of the stress field caused by fluid injection and resulting effects on injection induced seismicity. We develop an analytic solution to model an injection source in a three dimensional poroelastic medium of infinite extent. We use linear superposition to model a cylindrical injection that mimics an open borehole section rather than a single point source. The influence on induced seismicity is monitored via changes in the Coulomb failure function.

Our results indicate that poroelastic induced stresses have a direct impact on the triggering front of the induced seismicity. In particular during shut-in we find a significantly different position of the triggering front compared to predictions from pore pressure diffusion models. The calculated three-dimensional seismic event clouds are in good agreement with field observations.

Our findings emphasize the importance of poroelastic stress changes in addition to pore pressure diffusion effects in describing and analyzing injection induced seismicity.

Technical Session 14 – California East Geothermal: Hurdles to Successful EGS

Monday, June 29, 2015, 04:30 pm - 06:00 pm

Chairs: Joshua Taron & Nick Davatzes

ARMA 15-0175

Relative Importance of THM Effects During Non-isothermal Fluid Injection in Fractured Media

Mohammadreza Jalali[1], Keith F. Evans[1], Benoît C. Valley[2], Maurice B. Dusseault[3]

[1]*ETH Zurich,* [2]*University of Neuchâtel,* [3]*University of Waterloo*

Rock mass treatment using fluid injection is common in various industrial applications, including enhanced recovery methods in the oil and gas industry, rock mass pre-conditioning in the mining industry, and heat extraction in geothermal systems. Hydro-mechanical processes related to such injection are of interest, especially rock failure either through shearing of weakness planes or hydraulic fracturing of intact rock or pre-existing natural fractures. In many cases, the injected fluid is not at the same temperature as the rock and an additional thermo-mechanical effect develops that is rarely included in analyses. This is particularly true for geothermal application and thermal enhanced oil recovery methods. In addition, the presence of natural fractures and discontinuities in the host rock increases the complexity and heterogeneity of the system by adding a strong non-linearity to the transport processes. In such a situation, it is unclear a priori if the thermo-mechanical response is significant or not, compared with the hydro-mechanical one. An appropriate understanding of poroelastic and thermoelastic stress effects on the dominant conductive fracture systems is then crucial to characterize and understand the physical behavior of the system.

To assess the conditions under which the thermo-mechanical component cannot be neglected, induced thermoelastic and poroelastic stress effects on the elastic and failure behavior of a conductive fracture in an isotropic and homogenous impermeable medium is studied. A sensitivity analyses is performed using a fully coupled thermo-hydromechanical model, implemented via a combination of the finite difference method for pressure and temperature calculation inside the fracture and a displacement discontinuity method for the estimation of normal and shear displacement of the fracture plane as well as heat flux rate from the fracture into the impermeable rock.

The results show that the thermoelastic effect overwhelms the poroelastic effect adjacent to the injection well, whereas far from the injection well poroelastic effects dominate because the pressure front always moves faster than the heat front. In addition, the fracture becomes more susceptible to shear failure in the presence of both thermoelastic and poroelastic induced stresses for the case of cold fluid injection. The magnitude of the changes implies that an appropriate thermo-hydromechanical model is an essential key to address the physical behavior and potential failure of conductive fractures under thermal stimulation.

ARMA 15-0869

Three-dimensional Numerical Investigation of the Effect of Injection Method on Shear Stimulation of Enhanced Geothermal Reservoirs

Azadeh Riahi[1], Branko Damjanac[1], Zorica Radakovic-Guzina[1], Tatyana Katsaga[2]
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This paper presents the result of a series of three-dimensional numerical studies that investigate the response of enhanced geothermal reservoirs to injection during the stimulation phase. In these studies, the three-dimensional discrete fracture network is explicitly represented in the model. The numerical analyses are hydro-mechanically coupled, and thermal effects during the stimulation phase are disregarded. The sensitivity studies evaluate how the following aspects of the injection method can mprove the total shear-stimulated area: (a) staged injection compared to one stage injection; and (b) injection into cased borehole with multiple hydraulic fracture clusters vs. injection through open-hole completion. In addition, the effect of fracture size characteristics of the reservoir on the shear stimulation response is studied. It is observed that the technique used for injection of fluid has a significant effect on the total stimulated area in the reservoirs.

ARMA 15-0626

Mapping Permeability Tensors in Fractured Geothermal Reservoirs Using MEQ Data

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In the course of the creation of an Enhanced Geothermal System (EGS), injection wellhead pressure, flow rate and microearthquake (MEQ) data are crucial feedbacks recorded in order to characterize the evolution of subsurface fluid flow. However, one of the hurdles to a successful EGS development and operation is the lack of reliable evaluation for the initial and evolving hydraulic properties of the fractured reservoir. In the stimulation of an EGS reservoir, specific spatial conditions (e.g., location and direction) of fracture permeability in the field are vital in defining reservoir response during stimulation and then production. To constrain the initial and evolving permeability, we propose a model that maps the *in-situ* fracture-network permeability using the moment magnitude of individual MEQs, assuming that the induced seismicity is controlled by the Mohr-Coulomb shear criterion. The MEQ catalog of locations, fault plane solutions, and moment magnitudes are used to estimate fracture apertures of individual events/fractures that are a dynamic function of *in-situ* stress, fluid pressure, shear displacement and fracture size. The corresponding *in-situ* permeability tensors are computed and mapped at scales within the reservoir. Results suggest that the permeability magnitude largely depends on MEQ moment magnitude and fracture frictional properties while permeability direction is dominantly controlled by fracture orientation. The significance of this model lies in two aspects: (1) it allows abundant observations of MEQ to constrain the structure and distribution of *in-situ* permeability evolution; and (2) it implies the importance of determining *in-situ* geomechanical parameters (e.g., fracture orientation, fracture stiffness, dilation and friction) as another hurdle to a successful EGS creation and operation.

ARMA 15-0810

Use of Geodesy to Discriminate Deformation Mechanics in Geothermal Reservoirs

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There are several deformation mechanisms in EGS reservoir such as shear fracture displacement, fracture dilation, temperature driven shrinkage of the rock, water storage/leakage and pressure driven pore space expansion. Since each mechanism has its own deformation aspect, analyzing deformation data will give us various useful information in all stage of EGS project development from stimulation to commercial production. However, current analysis of EGS reservoir deformation is mostly focused on an indirect presumption of shear failure displacement by monitoring micro-seismic data. Surface geodesy signal, meanwhile, provides direct and various information of reservoir deformation including its shape (planar, spherical, tilt or extension), location of the deformation, magnitude and direction of the displacement (expansion, contraction, shear displacement or tensile dilation). However, it has its limitation that not all the deformation can be measured by typical resolutions of current surface geodetic techniques and also some of the surface deformation caused by different mechanisms may not be distinguishable because they give similar surface deformations. We explore the advantage that the inversion of multiple deformation signals provide when the signals are independent. This include distributed measurements of surface deformation and point measurement of surface displacement, strain, tilt and seismic signals. We identify the types of deformations, the characteristics of the signal distribution of each deformation type and the relationship between the magnitude of surface deformation and reservoir deformation in each type. In addition, to check the applicability, magnitude of surface deformation will be compared to the current resolution of surface geodetic tools. Coupled interpretation is also considered because it will give more accurate and detailed reservoir deformation behavior if the surface deformation is interpreted with the other data. Shear displacement have to be interpreted with micro-seismic, thermal shrinkage of reservoir have to be interpreted with heat gain rate of output flow and deformations due to water storage, leakage or fracture dilation have to be interpreted with water loss and pressure distribution.

ARMA 15-0658

Mechanisms of EGS Creation at The Geysers (California) revealed by seismic tomography, spatiotemporal evolution of the microseismic events and geomechanical simulations

Pierre Jeanne[1], Jonny Rutqvist[1], Antonio Pio Rinaldi[1], Lawrence Hutchings[1], Ankit Singh[1], Patrick F. Dobson[1]
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The Northwest Geysers EGS Demonstration Project started in 2011 at The Geysers (California). The goal was to create an EGS by injecting cool water at relatively low pressure into a known High Temperature (300-400C) reservoir affected by a network of small shear zones. To monitor the EGS development large scale hydrogeological and geomechanical field data were acquired before and during injection by monitoring microseismicity, reservoir pressure and surface deformations. Here, we present (1) tomography images of the seismic velocity (Vp, Vs) and attenuation (Qp, Qs) built from microseismic data recorded during the first 60 days of injection and (2) the spatiotemporal distribution of the injection-induced microseismic cloud over 270 days of active injection. The seismic tomographies highlight the degradation of the reservoir mechanical properties one a large scale within the reservoir (decrease in Vp and Vs), and reveal the presence of the injected water just around the injection well (increase in Qp). The spatiotemporal analysis of the microseismic hypocenter shows the development of a domain seismically quiet around the injection well surrounded by a spatial domain seismically active. The domain seismically active corresponds to the area where the degradation of the reservoir mechanical properties was observed, and the domain seismically quiet seems correspond to the area where the injected water flows. To understand and validate these observations, we built a 3D Thermo-Hydro-Mechanical (THM) model of the EGS, which accounts for changes in permeability as a function of normal stress and plastic shear strain. A numerical model was developed and calibrated by comparing the simulated THM responses to field observations. The results show that: (1) the aseismic domain is due to the presence of the injected cold water and to the thermal processes. This causes a cooling-stress reduction, which prevent shear reactivation and favors the fracture opening significantly increasing the permeability. This process is accompanied by aseismic plastic shear strain, which can be interpreted as slow slip events. (2) In the seismic domain, microseismicity is caused by the reactivation of the preexisting fractures due to injection-induced pressure increase. In this domain, permeability mainly evolves according to the effective normal stress acting on the shear zones. Indeed, the reactivations of the preexisting fractures within the shear zone have a low impact on its permeability. The main raison is that the initial permeability is already high (up to two orders of magnitude than the host rock).

ARMA 15-0214

Wellbore instability during plasma torch drilling in geothermal reservoirs

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By consider of this obvious development of research and technologies of geothermal resources, the number of wells, varied drilling depth and formation temperature of high temperature geothermal wells increases daily. However, so far the well control technology of high temperature geothermal drilling has not been focused carefully, the serious shortage of related technology and equipment retards the development of geothermal resources.
Wellbore drilling operation for any resources extractions and particularly for engineering geothermal systems (EGS) are subject to many uncertainties, ranging from those related to geology to those related to the drilling procedures. Since well drilling and related to the subsurface activities and also cost and time of it are subjects that they can include a variety of uncertainties can be systematically assessed.
Thermal plasma assisted drilling technology is often investigated to be used in geothermal well drilling operation, but there are many problems along with drilling depth increasing. One must consider reservoir conditions and enthalpy of the expected inflow into wells. Investigation of the wellbore instability in the case of drilling deeper in high-temperature geothermal systems has been induced by the application of plasma torch as a thermal assisted drilling in geothermal reservoirs is discussed. The wellbore instability analysis of thermal assisted geothermal wells drilling, it is found that to evaluate the possibility of the wellbore instability in focusing on the effect of heat transfer some necessary regulations should be fulfilled. This work also mentioned on laboratory experiments of plasma torch interactions and rock texture. Core size rock samples interact with temperature that generated from plasma torch with initiating and propagation fractures.
Present work focused on analyzing the thermal effects produced by plasma torch on rock physical parameters assisting the operation during the geothermal well drilling. Plasma torch can interact with rock texture continually and this could reduce the rock strength. In the presented theoretical model it is noticed that elasticity modulus and temperatures play special roles in thermal stress distribution. The results show that 4500 ^{0}C with 6MPa elasticity modulus is the best target for wellbore instability. On the other hand, 1500 ^{0}C with 38MPa elasticity modulus is a suitable target for stability of the borehole. In experimental work it is found that 7 to 10 seconds plasma torch traction with cylindrical specimen rock samples can cause effective thermal fractures and the related photos confirms this claim. Elasticity modulus and failure strength of all limestone samples are almost eliminated after 10 second of plasma torch traction with each one of them.

Technical Session 15 – Elizabethan AB
Multiscale Modeling

Monday, June 29, 2015, 04:30 pm - 06:00 pm

Chairs: Giovanni Grasselli & Andrew Bunger

ARMA 15-0304

A combined experimental (micro-CT) numerical (FDEM) methodology to study rock joint asperities subjected to direct shear

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Rock mass discontinuities represent planes of relative weakness and enhanced hydraulic conductivity and, thus, have a substantial influence on the hydro-mechanical behaviour of the overall rock mass. While the shearing of rock mass discontinuities has been extensively studied in the past, there remains uncertainty surrounding the mechanisms by which surface asperities deform and degrade during shear and how this degradation influences the aperture distribution. Although many studies have attempted to investigate asperity failure mechanisms, they have been hampered by the lack of appropriate visualization and modelling tools. In particular, until recently it was not possible to observe asperity damage without physically separating the joint specimen or explicitly modelling the development of damage during a direct shear test.
The objective of this paper is to explain a recently developed methodology to study asperity degradation mechanisms and rock joint geometry during shearing (Tatone 2014). The methodology combines the use of micro X-ray Computed Tomography (μCT) to non-destructively characterize sheared rock joint geometry with hybrid continuum/discontiuum modelling (FDEM) techniques to understand the stress conditions and failure mechanisms responsible for this geometry.
Selected results obtained using this methodology are then presented and discussed. Such results provide unprecedented insight into the rock joint shearing process, which will be of key interest to several areas of rock engineering and hydrogeology; including those concerned with preventing shear displacement (e.g., excavation, slope, and dam stability analyses) and those concerned with changes in hydraulic transmissivity resulting from shear displacement (e.g., EDZ around long-term radioactive waste repositories and reservoir stimulation via hydraulic fracturing).

ARMA 15-0229

Numerical study of crack coalescence in rock under quasi-static and dynamic loading by using the distinct lattice spring model

Chao Jiang[1], Gaofeng Zhao[1]
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The dynamic behaviour of crack propagation and coalescence in rock is investigated using the distinct lattice spring model (DLSM). Discontinuum based element model has been proven as a promising tool in the study of dynamic fracture in rock. As a newly developed tool, the distinct lattice spring model (DLSM), compared with classical discrete element model (DEM), has advantages on computationally efficiency and being free of micro parameters calibration. This study further applies the DLSM to investigate the dynamic cracking and coalescence behaviour in rock. First, the capability of the DLSM on modelling crack propagation and coalescence was verified against experimental data of central notched Brazilian discs (CNBD) tests. The simulation results on crack pattern and coalescence are in good agreement with the experimental observations. Following this, the influence of impact velocity on the crack pattern and coalescence behaviour were studied numerically. It is found that the impact velocity will both influence the topology of single crack propagation and coalescence behaviour. More specifically, when the loading rate increases the wing crack tends to be curvy and rough. Similar phenomena was observed in the new generated crack surface in the crack coalescence simulation. Besides 2D crack surface path information as from experimental test, the evolution of 3D topology of the crack under different loading velocities was

also observed by using the DLSM. It is found that the same surface crack pattern is reproduced by the 3D simulation, however, the crack growth in 3D space was not as our expectation, e.g. crack propagation front is very irregular and failure might appear ahead of the crack tip. Our results show that the it is of importance to consider the 3D crack propagation in rock engineering practice. Moreover, the evolution of kinematic energy and strain energy release during the crack propagation and coalescence under different loading speeds were investigated. The findings can be useful to provide better understanding of the failure of rock under dynamic loading such as blasting and earthquake. Following the numerical work, experimental work will be conducted to verify these findings.

Key words: Crack coalescence; dynamic loading; fracture mechanics; lattice spring model

ARMA 15-0460

Development of soil-water coupled NMM-DDA

Ryota Hashimoto[1], Tomofumi Koyama[2], Mamoru Kikumoto[3]
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In order to simulate the behavior of composite structures consisting of discontinuous blocks and ground simultaneously, the authors have developed an elasto-plastic NMM-DDA (combined Numerical Manifold Method and Discontinuous Deformation Analysis). However, to evaluate the long-term deformation behavior of the building as masonry structure caused by consolidation behavior of the ground, the coupled seepage-deformation behavior should be properly incorporated.

In this paper, a soil-water coupled code based on NMM-DDA for saturated ground was newly developed. The code consists of three governing equations, the equation of motion for the DDA part, the equilibrium equation and the continuity equation for the NMM part. In the formulation, the first and the second equations were combined using the contact treatment using penalty method similarly to the original NMM-DDA. Then, the equilibrium equation and the continuity equation for the NMM region was coupled with the effective stress concept based on *u-p* formulation. This coupling formulation enables the stability analysis of masonry structure on the saturated ground.

As a verification of newly developed simulation code, one-dimensional consolidation analysis was carried out. In the simulation, saturated soil column was modeled by NMM, and overburden load was applied by putting a DDA block on the column. The simulation results showed good agreement with the analytical solution of Terzaghi's consolidation equation, and the validity of the new code was confirmed.

ARMA 15-0430

A Calibrated Synthetic Rock Mass (SRM) Model for Simulating Crack Growth in Granitic Rock Considering Grain Scale Heterogeneity of Polycrystalline Rock

Kiarash Farahmand[1], Mark Stephan Diederichs[1]
[1]Queen's University

Understanding and quantification of fracture evolution and associated fluid flow behavior of continuous intact rock under hydro-mechanical loading is of utmost importance when designing and constructing a structure in or on rock. Numerical modelling is a popular means to study the damage-modified mechanical and hydraulic properties of rock under deformation, due to its advantages over expensive laboratory and in-situ experiments. A grain-based DEM-Voronoi technique is used to investigate the role of hydro-mechanical interactions on damage-permeability behavior of granitic rock. First, the micro-mechanical parameters of the model is calibrated to Lac du Bonnet granite such that the model reproduces the physics similar to that of the rock during compression and tension. The calibration procedure is based on categorizing a set of input parameters that controls the elastic and fracture behavior of the model. Subsequently, sensitivity analysis is performed to evaluate the effects of various micro-parameters values on yielding correct rock response during compressive and tensile loadings. Afterward, a series of biaxial compression tests are simulated to examine the role of micro-cracking and pore pressure evolution on altering fluid flow properties of

rock while two cases of one-way and two-way coupled hydro-mechanical analyses are taken into account separately.

The numerical experimentations demonstrate the capability of discrete element-Voronoi model to mimic the pre- and post-failure response of brittle materials and corresponding rock permeability. The calibrated model very accurately predicts, in a quantitative sense, the macroscopic properties of real granite such as elastic properties, damage thresholds (crack initiation and interaction stresses), peak strength (tensile and compression strengths), triaxial strength envelope (friction angle and cohesion) and dilation angle. Calculated permeability evolution of the model in pre- and post-failure states compares well with experimental observations, in which the permeability decreases by 2 orders of magnitude from its non-stressed permeability (5×10^{-20}) prior to rupture of rock, while interaction of cracks leads to an additional 3 orders of magnitude increase for post-failure permeability. It is also demonstrated that coupling between the pore fluid pressure and solid constitutes of rock plays an important role on cracking-driven failure process and resultant permeability of brittle materials.

Keywords: Stress-induced permeability change, brittle failure, discrete element method, Voronoi joint, calibration process, and sensitivity analysis.

ARMA 15-0716

Simple modeling of time-dependent behavior for normally consolidated soil to structured soil

Teruo Nakai[1], Hossain Shahin[2], Hiroyuki Kyokawa[3]
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Simple models to describe time-dependent behavior of geomaterials in 1D and 3D stress conditions are presented. Most of the previous viscoplastic models have been formulated based on the over-stress theory or the non-stationary flow surface theory. However, these models have some shortcomings in their formulation such as including non-objective time variable, lack of loading condition and others. In the present paper, brief explanation of the previous viscoplastic models is firstly given in one-dimensional condition to understand their concept easily. After then, a new time-dependent model is presented which is formulated not using the above-mentioned viscoplastic theories but utilizing the subloading surface concept by Hashiguchi (Hashiguchi, 1980) and paying attention to the experimental results, which show that the normally consolidation line (NCL) and the critical state line (CSL) on the $e - \ln\sigma$ plane shift depending on the strain rate. The present model can describe various time-dependent behaviors of normally consolidated soil to naturally deposited soils (structured soils) in the same manner without violating the objectivities. To describe the behavior of structured soil, a state variable ρ which represents the influence of density and the other state variable ω which represents the bonding effect are introduced. After the formulation is explained in one-dimensional conditions in order to understand the fundamental concepts of modeling, the one-dimensional model is extended to a three-dimensional one using the t_{ij} concept (Nakai and Mihara, 1984). The validity of the present models is verified using various kinds of simulations of time-dependent behavior in one-dimensional and three-dimensional conditions.

ARMA 15-0691

Numerical study on the heterogeneities of rock material under Brazilian test

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The tensile strength of rock material is generally obtained through the most common indirect approach-Brazilian test. Laboratory tests show that various splitting lines along the loading direction have been observed in Brazilian test. This is mainly due to the fact that the majority of real rock materials encountered in Civil and Mining Engineering are normally not homogeneous materials. In most laboratory tests, the main features of macro-fracture patterns within heterogeneous rock

materials may vary from specimen to specimen owing to the differences of local heterogeneity; also the same rock material with low porosities behave more brittle than those with high porosity, being regarded as hard rock. These experimental work normally can only demonstrate the macro-scale behaviours of heterogeneous rock. Thus, numerical simulation is conducted to study the heterogeneities of rock material under Brazilian tests in this paper. This is achieved through a well-developed distinct lattice spring model (DLSM). One of the main features of DLSM is that it can explicitly represent the microstructure of rock materials, which enable DLSM to model mechanical fracturing problems and to study the effects of heterogeneity on rock samples under Brazilian test. The influences of porosity, various types of distributions of pores and fractures inside rock samples are taken into account, with further analysis given to the tensile strength, the final failure modes and the process of tension fracturing of heterogeneous rock samples. Numerical study demonstrates that, porosity and the distribution of pores and fractures contribute to the divergence of tensile strength and the final failure mode. Rock samples with lower porosities are featured with higher tensile strength and more brittle behaviours, and vice versa. The local heterogeneities indeed contribute to different final failure patterns, with limited influences on the tension strength.

KEY WORDS
Brazilian test; Tensile strength; Heterogeneous rock; Distinct lattice spring model; Porosity; Weibull distribution

Technical Session 16 – Elizabethan CD
Coastal Subsidence

Monday, June 29, 2015, 04:30 pm - 06:00 pm

Chairs: Bogdan Orlic & Karin Thienen-Visser

ARMA 15-0098

Subsidence due to gas production in the Wadden Sea: How to ensure no harm will be done to nature

Karin Thienen-Visser[1], Annemarie Muntendam-Bos[2], Jaap Breunese[1]
[1]TNO - Geological Survey of the Netherlands, [2]State Supervision of Mines

The Wadden Sea is a shallow tidal sea in the north of the Netherlands. The area has been inscribed on the UNESCO's World Heritage list since 2009. Also in the Wadden Sea, gas production is ongoing since 1986. Since 2006 additional gas fields are being produced. Due to the sensitive nature of this area the gas fields are being produced within the "effective subsidence capacity" for the two tidal basins affected with gas production induced subsidence. Effective subsidence capacity is defined as the maximum averaged subsidence rate available for planning of human activities. It is determined by subtracting the natural subsidence volume rate (relative sea level rise and shallow subsidence) from the sedimentation volume rate. We present a method to monitor the effective subsidence capacity and ensure that subsidence is below the long term (18.6 years) limit of acceptable subsidence, thus preventing damage to the protected nature. The role of sedimentation volume rate, relative sea level rise and subsidence volume rate due to gas depletion are taken into account including their uncertainties in a probabilistic method. The rate of subsidence is obtained by modelling the gas fields that cause subsidence in two tidal basins in the Wadden Sea. Both different dynamical reservoir models as well as different geomechanical models are taken into account to model the epistemic uncertainty of subsidence. The volume rate of sedimentation is derived using the results of numerical modeling for two other tidal basins in the same Wadden Sea. Finally, different climate models are used to construct scenarios of relative sea level rise. In the Wadden Sea, gas production will be ceased or reduced by the governement if it is likely that the limit of acceptable subsidence is exceeded. The results of the probabilistic method indicate that the probability of exceeding the level of acceptable subsidence is low up to 2012 (< 6%) and increases as time increases due to the increase in relative sea level rise. The probability of exceeding the acceptable subsidence limit for the period 2012 to 2050 is 8% for the tidal basin called Zoutkamperlaag and 2,5% for the

tidal basin of Pinkegat for climate scenarios that fit the current relative sea level rise observations on the Dutch coast. The exact probabilities depend strongly on the values for relative sea level rise obtained through climate scenarios. Warm climate scenarios cause higher probabilities but are not supported by recent observations of relative sea level rise on the Dutch coast.

ARMA 15-0375

Surface subsidence induced by hydrocarbons extraction, and the potential for time-dependent ground deformations

G. Marketos[1], R.M.A. Govers[1], C.J. Spiers[1]
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Pore pressure reduction due to hydrocarbons extraction from gas reservoirs causes compaction of the reservoir accompanied by a redistribution of stresses in the surrounding rock mass, leading to sub-surface deformations that are often registered at the surface as subsidence. There is evidence to suggest that the induced sub-surface movement in some of the Netherlands' larger gas fields (the motivation behind the study) are time-varying. The sandstone reservoirs in question are overlain by relatively thick layers of rocksalt, which flows viscoelastically when shear stress are applied to it. For this reason, rocksalt flow has been proposed as a mechanism to explain the observed time-dependence.

The work reported here aims to understand the mechanisms by which viscoelastic rocksalt flow can cause surface displacements and to assess whether the magnitude of the resulting displacements can be significant over timescales similar to those observed in the field. Finite Element analyses of idealised reservoir geometries and simplified geological models will be employed for this purpose, with the aim of avoiding complexities that can mask the underlying processes and phenomena. The models explored allow for the effects of reservoir shape, salt layer thickness, elastic properties contrast between different layers, and rocksalt material properties to be systematically investigated and isolated. The results will help confirm whether rocksalt-induced flow is the dominant mechanism by which time-dependent surface subsidence effects arise. While focused on indurated rocks systems at depths of around 3 km, the conclusions from this study will also be relevant to other problems of cavity contraction or expansion within or in the vicinity of material layers that are viscoelastic.

ARMA 15-0618

Long-term compaction behavior of Permian sandstones – An investigation into the mechanisms of subsidence in the Dutch Wadden Sea

Sander Hol[1], Antony P. Mossop[2], Arjan J. van der Linden[1], Pedro M. M. Zuiderwijk[1], Axel H. Makurat[1]
[1]*Shell Global Solutions International B.V.*, [2]*Nederlandse Aardolie Maatschappij B.V.*

In this contribution, we report on the effect of production-induced reservoir compaction, using core material from a Permian sandstone reservoir located at the Dutch Wadden Sea coastline, at a depth of ~3700 m TVDMSL. To assess the nature of the compaction mechanisms that operate in these reservoirs, and hence better constrain predictions of subsidence rate and magnitude, we have carried out more than 30 long-term pore pressure depletion tests on sub-samples taken from the extracted core material. Our laboratory data show that pressure depletion results in total strain of 5·10-3 - 15·10-3 over the duration of the experiment of 5-12 weeks, with approximately 80% of the total strain response being rapid, and 20% time-dependent. The response is dependent on porosity and stress state, but seems rather insensitive to temperature, and pore fluid composition. Our work shows that while volumetric compaction of the sandstone reservoirs could be responsible for the magnitude of the subsidence observed in the Wadden area, it cannot directly explain the observed temporal relationship between subsidence and reservoir pressure decline, or at least not without some rescaling factor. Instead, other mechanisms such as salt flow or water-leg compaction should also be considered.

ARMA 15-0436

Rate type isotach compaction of consolidated sandstone

Hans Waal[1], Karin Thienen-Visser[2], Jitse Pruiksma[2]
[1]State Supervision of Mines, [2]TNO

Results from a series of laboratory experiments are presented that demonstrate that consolidated sandstone reservoir rock shows rate type deformation behaviour, similar to that observed on unconsolidated sandstones and soils. This can have significant relevance for the prediction of reservoir compaction, surface subsidence and induced seismicity caused by natural gas production.

As long as loading is carried out at a constant stress rate, the rock samples investigated show more or less linear elastic behaviour during uniaxial compaction experiments. This suggests that the effect of loading rate on the uniaxial compressibility can to first approximation be ignored. The present experiments were however specifically designed to investigate the relevance of creep and rate effects. During the experiments loading rates were stepwise increased and decreased over several orders of magnitude. Loading was resumed after extensive creep periods at constant stress and after partial unloading. Some of these procedures were combined within a single experiment. Strongly non-linear stress-strain behaviour resulted, demonstrating that rate effects can play an important role in the deformation of consolidated sandstones.

The experimental results are described well by a modified isotach version of the rate type compaction model (RTCM) previously developed to describe the compaction behaviour of unconsolidated sandstone. This modified version of the original RTCM elegantly solves a limitation of its predecessor. The stress-strain curve can now be calculated for the complete experiment with varying loading rates whereas the previous version only allowed calculations for piece-wise constant loading rate intervals.

The rate type isotach compaction behaviour observed in the laboratory experiments could potentially explain the non-linear relation between subsidence and pressure drop observed in a number of well documented field cases.

ARMA 15-0096

On the Use of Double Differences in Inversion of Surface Movement Measurements

Peter Fokker[1], Karin Van Thienen-Visser[1]
[1]TNO

Surface movement data can be used in data assimilation or inversion exercises to improve the level of knowledge of a compacting reservoir. Traditionally, optical leveling is used to first obtain benchmark heights with respect to a geodetic datum, of which the subsidence rate is then determined by subtracting values at different times. The latter are subsequently used in the data assimilation. We have designed, implemented and tested a new algorithm that uses measured height differences directly, without having to translate them to heights with regard to a geodetic reference level. This bypassing of the intermediate step has a number of advantages. In the first place, the measurement points are independent. This is an issue when the full covariance matrix is not taken into account when using interpreted benchmark heights – which is the usual procedure because the covariance values are often not available. In the second place, the accumulation of inaccuracy of the difference measurements, which have to be connected to a stable benchmark over multiple connected benchmark pairs, is circumvented. This makes the new method more accurate. Finally, the new method is less error prone. Individual errors in difference measurements do not propagate into many interpreted heights.

The procedure was applied to a synthetic field of which the compaction coefficient and the eastern border of the compacting area were assumed to be subject to considerable uncertainty. The procedure using the measured height differences directly was proven to be better than the traditional procedure.

The accuracy of the inverted numbers depend on the accuracy of the measured data. This was shown by three cases with different levels of noise added to the synthetic data. The constraining action of the inversion could be judged by the reduction in standard deviation between prior and estimated values for the different adjusted parameters. An additional case was constructed in which a level of

autonomous movement was incorporated. The amount of autonomous movement could be estimated, and for the other parameters, comparable numbers as for the corresponding exercise without autonomous movement were obtained.

ARMA 15-0307

Redistribution of Stresses due to Drilling and Depletion Using Different Plasticity Models

Sherif Akl[1]
[1]Cairo University

Oil companies are forced to seek deep water prospects with any new conventional resources are getting harder to find and existing ones are running out. In such regions, deep layers are composed of fine sediments, dumped by rivers as in the Gulf of Mexico (GoM) and the Mediterranean. These formations are relatively weak and insufficiently lithified. It is debatable whether these formations are considered hard soils or soft rock. However, it is certain that such formations exhibit complex plastic behavior and anisotropic stress strain response (Abdulhadi et al., 2009; Akl, 2010) and ought to be modeled carefully with adequately representative constitutive relations. Figure 1 shows the inward radial deformations of a typical vertical wellbore using poroelastic and poroplastic models. The figure shows significant influence of plasticity on wellbore deformations.
When advanced plastic models are used, such as the Modified Cam Clay (MCC; Roscoe and Burland, 1968); typical plane strain models in wellbore analysis show significant redistribution of vertical stresses. Figure 2 shows a zone around the wellbore cavity wall where vertical stresses decrease substantially as a result of plastic hardening. This fact is not in accordance with conventional analytical methods of wellbore analysis and stress predictions around reservoirs where vertical stresses are considered constant throughout the depletion process (Zoback, 2007; Dunayevski et al., 2012).
This goal of this paper is to assess the plastic redistribution around wellbores by comparing the results of 2D plane strain models to that of 3D models of vertical wellbores using both poroelastic and poroplastic models. These vertical stress perturbations are also expected on a larger scale around depleting/inflating reservoirs when plastic models are used (Akl, 2014). A 2D plane strain model is used to simulate a hypothetically extended reservoir being depleted below substantial layers of plastic sediments. Different plasticity soil models are used to capture the behavior of unlithified sediments such as: Drucker Prager Model (DP, Modified Cam Clay Model (MCC), and the MIT-E3 model (Whittle and Kavvadas, 1994). The MIT-E3 model has been calibrated to the behavior of GoM sediments by Whittle and Sutabutr (2005). This model is proven to capture the inherent and stress induced anisotropy of naturally sedimented formations (Akl and Louis, 2013). These comparisons as well as a proper assessment of the plastic redistribution of stresses lead to a better understanding of surface/seabed deformations in deep sea regions.

Technical Session 17 – California West
Hydraulic Fracture Simulation

Tuesday, June 30, 2015, 08:00 am - 09:30 am

Chairs: Ivan Gil & Azadeh Riahi

ARMA 15-0279

Study of multiple fracture interaction based on an efficient three-dimensional displacement discontinuity method

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Study of fracture interaction of multiple fractures based on a three-dimensional displacement discontinuity method

In recent years, production of tight oil and shale gas has increased exponentially in the United States. Multiple fracture treatments in horizontal wellbores are becoming a prevalent approach to economically develop unconventional reservoirs. A better understanding of multiple fracture growth is essential for accurately predicting fracture geometry. Mechanical interaction between multiple fractures, also referred to as stress shadow effects, is a critical factor controlling fracture geometry and inducing complex fracture geometry.
In this paper, we describe efforts to create a computational efficient model that is accurate for multiple, three dimensional fracture problems. The accuracy of a fast pseudo-3D method (Olson, 2004) for describing fracture interaction is investigated through comparing with a fully 3D displacement discontinuity method. Results demonstrate that the pseudo-3D solution underestimates the mechanical interaction between nearby fractures. The apertures of both interior and exterior fractures given by the pseudo-3D method are larger than the fully 3D solutions. However, 3D DDM is computationally far more expensive than the pseudo-3D method because a) more elements are required to describe a fracture in three-dimension and b) the computational cost per element is higher in 3D. We show that using 1 element in the fracture height direction with the standard 3D equations is unacceptably inaccurate, but by employing an analytically-based correction factor, that accuracy can be significantly improved, eliminating the need to extra elements for height-contained hydraulic fracture problems. The higher per element computation cost in 3D is largely the result of the fact that the 3D displacement discontinuity method has three unknowns (opening, strike-slip shear and dip-slip shear). Further speed advantage is gained by dictating all fractures must be vertical, which allows elimination of equation components related to the dip-slip shear. We demonstrate how this model can be applied to problems of multiple hydraulic fracture propagation in horizontal wells.

ARMA 15-0126
Effect of Fracture Breakdown Pressure on Multicluster Hydraulic Fracturing Treatments

Hongren Gu[1], Bruno Lecerf[1], Xiaowei Weng[1], Olga Kresse[1]
[1] *Schlumberger*

The success of unconventional reservoir development relies on the technology of multistage hydraulic fracturing in horizontal wells. In each stage, multiple perforation clusters are often used to create multiple fractures to provide adequate drainage along the entire horizontal well and, at the same time, to achieve economic goals. However, the production contribution from each perforation cluster has been found highly uneven, with 40% of the perforation clusters contributing little to no production.
One of the reasons for the low cluster efficiency is that effective fractures are not created from all the perforation clusters. It is well known that the fracture initiation pressure is higher than the horizontal minimum in-situ stress. Field observations have shown that the magnitude of fracture initiation pressure can vary significantly along a horizontal wellbore. Both the magnitude and the variation of fracture initiation pressure can cause ineffective fractures and low perforation cluster efficiency.
A computer hydraulic fracture simulator was used to study the initiation of multiple fractures from a horizontal well. The measured initiation pressures from actual fracturing treatments in horizontal wells are used in the simulation. The simulation results show that only a limited number of fractures can be generated for a given pump rate, independent of the number of the perforation clusters available in a stage. The number of fractures depends on the magnitude and the variation of fracture initiation pressure. The simulator has also been used to show cluster efficiency can be improved by perforation placement design based on completion qualities, as well as by advanced diversion technology. Based on the results from this study, guidelines are provided to achieve high cluster efficiency for effective fracture coverage in multistage fracturing treatments.

ARMA 15-0558
Simulation of Simultaneous and Zipper Fractures in SHALE Formations

Varahanaresh Sesetty[1], Ahmad Ghassemi[2]
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Horizontal well hydraulic fracturing technology can help develop unconventional petroleum resources. Today, industry uses simultaneous and sequential fracturing techniques in horizontal petroleum well stimulations. To achieve successful and desired stimulated rock volumes and fracture networks, one must understand the effect of fracture spacing, various rock and fluid properties on stimulation to minimize the risk of unwanted fracture geometries.
This paper describes the development of a fracture model based on displacement discontinuity method for simulating multiple fracture propagation in simultaneous and sequential hydraulic fracture operations. The sequential fracturing model considers different boundary conditions for the previously created fractures (constant pressure restricting the flow back between stages [1] and proppant-filled [2]). A series of examples are presented to study the effect of fracture spacing on fracture geometry and stimulated rock volume. The model is also used to compare the conventional zipper fracturing technique (i.e. fracturing multiple horizontal wells sequentially) with modified zipper fracturing technique [3]. The results highlight the fracture geometry and stimulated rock volume to achieve optimization of fracturing process. The paper also discusses the effects of rock anisotropic characteristics of shale on the results.

ARMA 15-0439
A 2D Experimental Method with Results for Hydraulic Fractures Crossing Discontinuities

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We present new experimental methods and results for two-dimensional (2D) hydraulic fracturing experiments investigating the interaction and crossing of a hydraulic fracture with a pre-existing frictional discontinuity (which can represent a natural fracture, fault, or bedding plane). Previous hydraulic fracturing experiments described in the literature have grown three-dimensional (3D) penny-shaped fractures toward planar frictional interfaces or have grown complex fractures through a network of natural fractures. The 2D experimental results given in this paper include direct measurement of fracture path along with fracture and interface displacement. This data is compared directly to results from a 2D numerical hydraulic fracture model, overcoming the problem of comparing experimental results that involve growing a 3D fracture with 2D model results. The results are compared to several published crossing criteria.
The 2D experimental method involves propagating a hydraulic fracture from the centre of a 350 x 350 x 50 mm rock sample. The sample is subjected to in-plane stresses orientated such that the hydraulic fracture extends horizontally from a pre-slotted borehole, penetrating through the entire thickness of the sample plate (the 50 mm dimension) and extends to intersect a pre-existing vertical discontinuity in the sample. Figure 1 contains a diagram showing the sample and the experimental configuration used in a polyaxial load frame. The out-of-plane normal stress acts to seal the sample faces with the sample sandwiched between PMMA shims with sheets of transparent vinyl acting as gaskets. These transparent shims allow continuous digital video records to be made of the fracture growth and fracture interaction with the vertical discontinuity. Displacement of a grid drawn onto the sample face is measured by optical analysis methods, allowing the fracture and interface opening to be measured to better than 10 micron resolution. The data provide information about fracture crossing/arresting, path, fracture and interface displacement with time, fluid penetration length into the discontinuity and timing and length of re-initiated fractures. Figure 2a contains an image from each of the cameras showing the sample containing the notched borehole and the pressurized and growing hydraulic fracture. Figure 2b shows the corresponding injection pressure and the fracture width evolution near the borehole.

The mechanics involved in a hydraulic fracture interacting with a natural fracture have been extensively studied because this process produces a number of first order effects on fracture growth. The crossing interaction can result in branching, offsetting and even blunting of the hydraulic fracture tip, significantly changing the fracture growth, excess pressure, and width. A verified method to predict the path during a crossing interaction is therefore necessary in any fracture stimulation model.

A dataset of 2D experimental results enables direct verification of 2D fracture models, which can then be used to carry out parametric studies in order to verify existing crossing criteria or to develop new ones for design purposes. The new ability to grow 2D hydraulic fractures in the lab and directly measure their path and displacement (including of interfaces they interact with) is a significant experimental advance. The 2D results provided are also directly applicable to hydraulic fracture height growth problems where the fracture is much longer than it is in height and the vertical growth occurring at a cross section of the fracture can be studied using a 2D geometry.

ARMA 15-0121

Investigation of Shear-Induced Permeability in Unconventional Reservoirs

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The interaction of hydraulic fractures with the pre-existing natural fractures may play a major role in increasing productivity from unconventional formations. When a hydraulic fracture meets a natural fracture, the hydraulic fracture can cross the natural fracture or be arrested. The natural fracture may be eventually opened if pressure inside the fracture exceeds the closure stress acting on natural fracture. If the natural fracture is permeable, fracturing fluid can leak from the hydraulic fracture into the natural fracture causing elevation of pore pressure in the natural fracture and reducing the normal stress acting on the natural fracture, which could also lead to shear failure or slippage along the natural fracture plane. Shear slippage causes dilation due to mismatching of the fracture surfaces, increasing fracture conductivity and enhancing fluid flow deeper into the natural fracture. The conductivity of unpropped shear-induced fractures can play an important role in enhancing the productivity from ultra –low permeability formations like shales.

In this paper, we first evaluate analytically the shear slip condition and its propagation along a natural fracture under remote normal and shear stresses. Analytical approximations under some limiting conditions are considered. A rigorous 2D numerical model based on coupling between rock deformation using Displacement Discontinuity Method and fluid flow in the fracture is then described. The results of numerical simulations are presented and compared with analytical predictions in the limiting cases. The details of modeling approaches are presented including elasticity, fluid flow equations, failure criterion (frictional law), pressure drop along the fracture, change of permeability due to pressure change and shear slip, etc. Numerical examples including the effect of rock stress anisotropy, initial natural fracture conductivity, fluid properties on evolution of fluid and slip fronts along the natural fracture and associated permeability enhancement will be presented.

ARMA 15-0074

Hydraulic Fracture Design Optimization for Infill Wells: An Integrated Geomechanics Workflow

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Natural fractures can reactivate upon stimulation and interact with propagating hydraulic fractures. This interaction usually creates complex, productive fracture networks that can remain open during production. Geomechanical models quantify key parameters that control the extent and characteristics of the Productive Stimulated Rock Volume (P-SRV) in naturally fractured reservoirs.

Once calibrated against field observed microseismicity, these models can be utilized to optimize stimulation design parameters for infill wells or re-fracturing operations. In this paper we present stimulation design optimization within the framework of a coupled "Geomechanics-Microseismic-Reservoir-Discrete Fracture Network (DFN)" workflow. We focus on a field data set, obtained from two hydraulically fractured wells in Barnett formation. After the models are calibrated against microseismic data, a series of simulations are conducted to understand key parameters that control the P-SRV of a planned infill well. In these simulations both stimulation design parameters (e.g. pumping time/rate, fluid type, proppant volume/type) and well architecture (e.g. stage number, stage length, well orientation) are varied as their impact on P-SRV is quantified. Our results show that extent of P-SRV in a naturally fractured reservoir can be controlled. The workflow introduced in this paper can guide field operations and optimize stimulation design to (i) maximize P-SRV of an infill well (ii) limit/control fracture communication between infill wells and existing producers.

Technical Session 18 – California East
Repository Issues for Nuclear Waste Disposal

Tuesday, June 30, 2015, 08:00 am - 09:30 am

Chair: Frank Hansen

ARMA 15-0478

Microseismicity induced in the Opalinus Clay by a gallery excavation in the Mont Terri underground rock laboratory

Yves Le Gonidec[1], Christophe Nussbaum[2], Joël Sarout[3], Jérôme Wassermann[4], Paul Bossart[2]
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In 2008, a new gallery, called Ga08, was excavated in the Mont Terri rock laboratory (Switzerland) to join a pre-existing end-face of an earlier gallery, called Ga04. The excavation method, using a particular excavation machine, hydraulic drum cutter, mounted on an excavator machine, allows for a smoother excavation that limits the extent of the induced excavation damaged zone. The junction between two galleries offered us an unique opportunity for characterizing the development of a fresh excavation damaged zone in time and in space by using different geophysical methods. We focuses here on the acoustic experiments we have conducted during the gallery excavation.

Arrays of acoustic sensors have been specifically designed to be introduced, from the Ga04 end-face, in horizontal boreholes to monitor an argillaceous rock mass segment of 8 m in length. In the one hand, active experiments, called "seismic surveys", consisted in emitting high frequency pulses to sound the medium with a controlled acoustic source to highlight the P-wave velocity field. In the other hand, passive experiments, called "microseismicity", used the same acoustic arrays to detect acoustic emissions induced in the rock mass segment by damage processes due to stress redistribution around the freshly excavated Gallery Ga08.

From the acoustic surveys, we highlight the transversely isotropic P-wave velocity field of the rock mass. We show that it can be used to efficiently locate the controlled acoustic sources and validate the localization procedure (based on first arrival time inversion). From the large data set of recorded acoustic emissions, we first identify only few stress-induced microseismic events (MSEs) with confidence by developing a restrictive but efficient multi-step filtering method. We then apply the location procedure to these MSEs and deduce their spatial distribution. We show an asymmetric geometry of the excavation damaged zone around the excavated gallery: no detectable microseismic activity is observed in the sandy facies sidewall and a burst of MSEs locates in the shaly facies sidewall followed by two smaller bursts which occurred when the excavation procedure was stopped.

In a further step of the data analysis, we deduce the damage mechanisms associated to the last two bursts of MSEs, based on the determination of focal mechanisms. The first burst of microseismic

activity, which sources locate ahead of the excavation front, is associated with a dominant double-couple component (DC): a bedding plane activation is suggested, that is, shear along bedding planes and associated wing-cracks. This damage mechanism is confirmed by structural observations of the fracture network previously impregnated by resin for a better imaging. The second burst locates inside the sidewall of the gallery, and is associated to a dominant compensated linear vector dipole (CLVD), which is confirmed by extensional fracturing commonly observed in the sidewall where the tangential stresses exceed the rock strength due to the stress redistribution around the gallery.

As a conclusion, this study allows identifying and discussing five major factors that seem to control the MSE source mechanisms: shale lithology (sandy facies vs. shaly facies), geometry of the pre-existing geological fault systems, rock anisotropy (bedding planes), gallery orientation with regard to the excavation direction, and orientation of the main compressive stress.

ARMA 15-0540

DECIMETER-SCALE ANALYSIS OF GEOLOGIC HETEROGENEITY IN A BRITTLE-DUCTILE SHEAR ZONE, ÄSPÖ HARD ROCK LABORATORY, SWEDEN

Aaron Fox[1], Anders Winberg[2], Henrik Drake[3]
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The Äspo Hard Rock Laboratory is a key asset in research into the science and engineering of safe underground storage of spent nuclear fuel in Scandinavia within fractured granitic rock. During a previous underground solute transport experiment (TRUE Block Scale Experiment) an extensive characterization of moderate-scale (~100 – 500 m) fractures and deformation zones was performed. The construction of an experimental tunnel (TASS), immediately adjacent to the TRUE Block Scale rock block, intersected a key conductive feature (Structure #20) of the TRUE Block Scale experiment and offered a unique opportunity to characterize the heterogeneity within a brittle-ductile shear zone at very high (centimeter to decimeter) resolutions, also allowing comparison of information collected in cored boreholes. Utilizing high-resolution HDR and UV digital images alongside traditional mapping and sampling techniques, the study investigated the lithologic, hydraulic, structural geology, and hydraulic characteristics of Structure #20, with the goal of further developing the understanding of the geology of similar structures that might be encountered during repository construction elsewhere in Sweden and how (pilot) borehole information relates to that subsequently collected in a drill and blast tunnel.

ARMA 15-0057

Transferring the geomechanical behaviour of Opalinus Clay observed in lab tests and the Mont Terri URL to assess engineering suitability at a potential repository site

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Opalinus Clay is the designated host rock for a high-level radioactive waste repository and a candidate host rock for a low- and intermediate level waste repository in Switzerland. Geomechanical core testing demonstrated that the Opalinus Clay is a moderately overconsolidated claystone which may be considered as either a stiff clay or soft rock. It exhibits stress-dependent and anisotropic elastic and strength properties, with strain localization and distinct strain weakening after failure, moderate swelling and complex behavior when partially saturated.

For the site-selection process, it is necessary to address the engineering feasibility for geological siting areas with potential repository depths between 400 to 900m below ground (b.g.) in Northern Switzerland. It is a key step to identify the maximum depth, at which construction of a repository according operational safety and long-term safety requirements can be assured. Extensive experience on the engineering performance of the Opalinus Clay has been gained from excavation works in the Mont Terri underground laboratory (URL) at 300m b.g., located some 50 to 100km to the west of potential repository sites. A compilation of convergence measurements from 17 locations at the URL shows that diametral strain is strongly influenced by the stress field and tectonic discontinuities. Pore fluid pressure measurements and deformation sensor data indicate a large plastified (or excavation damage) zone up to 6 tunnel radii from the tunnel axis.

Geomechanical core testing indicates lower strength and stiffness properties for samples from the Mont Terri URL when compared with samples from greater depths at potential repository sites. This is due to differences in the current and maximum burial depth rather than a significant variability in mineralogy. In addition to these site-specific rock properties, tectonic overprint and stress conditions are also different at potential repository depths, implying that tunnel performance at Mont Terri cannot directly be transferred to the siting regions in Northern Switzerland.

Based on the geomechanical data base, we present an overview of the simplification and abstraction steps taken to assess the engineering feasibility of underground structures at greater depths. These include: 1) simplification of a complex constitutive law to a Mohr-Coulomb failure criterion with two geomechanical input data sets to honor depth-dependent rock properties, 2) formulation of continuum rock models to account for variable tectonic overprint, and 3) using tunnel performance at Mont Terri and other underground structures in similar rocks as guidance for transferability to different conditions.

ARMA 15-0393

Computer modeling applied in the design of underground salt caverns opened by solution mining for gas storage

Pedro Costa[1], Alvaro Costa[2], Edgard Poiate[2], Claudio Amaral[2], Andre Pereira[3]
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This paper discusses the design of underground salt caverns, opened by solution mining, for CO2 Sequestration in Brazil, considering the large regional thicknesses and continuity of rock salt overlying the pre-salt reservoirs. The rock salt has negligible porosity when compared to other geomaterials, which ensures excellent sealing to most fluids and gases, even under high pressures. Rock salt is also subject to the phenomenon of visco-plastic creep deformation which develops in the time domain the relaxation of the deviatoric or shear stresses, to the condition of a steady-state equilibrium with constant creep strain rate and can tolerate high levels of strain without develop structural damage of its mineral skeleton. This phenomenon can be observed in nature in the sedimentary layers intercepted by salt domes or other structures associated with the natural movement of salt. Another phenomenon associated with the salt rock is the process of self-healing, where cracks and faults are self-healed with time. Taking advantage of these physical-chemical and structural properties of rock salt, caverns developed by solution mining in salt domes may be used for storage of hydrocarbons and other products, as for example CO2. Special attention is given to the geomechanical structural design of the caverns using computer codes specially developed for the simulation of excavations in salt rock formations, considering validated constitutive creep laws obtained by lab tests under differential stresses and temperatures. These computer codes and methodology have being used in the design of several clusters of caverns for brine production, design of the underground conventional potash mine and also in the design of the pre-salt oil wells, for the exploration and production of the pre-salt reservoirs. Despite being a technology already dominated worldwide, the use of underground storage of CO2 in salt caverns for offshore application in deep and ultra-deep water is unprecedented.

ARMA 15-0210

Sealing capacity of a seal system in rock salt – Hydraulic impact of the EDZ long-term evolution

Oliver Czaikowski[1], Klaus Wieczorek[1], Uwe Hertes[1]
[1]*GRS*

On behalf of BMWi, the national funding organisation for R&D work related to radioactive waste management in Germany, GRS is investigating sealing and backfilling materials planned to be utilised in salt formations. The program aims at providing experimental data needed for the theoretical analysis of the long-term sealing capacity of the seal system, including performance of the excavation damaged zone (EDZ) (Czaikowski et al. (2013), DOPAS (2012)).
According to current R&D work on the salt option, the shaft and drift seal systems considered in Germany comprise seal components consisting of MgO and cement based salt concrete (Mueller-Hoeppe et al. (2012)).
With respect to EDZ evolution, the following 3 scenarios are conceivable:
There is no contact between the EDZ and brine/vapor,
There is brine/vapor flow into the sealing system, as a result the EDZ pore space will be partially saturated,
The EDZ or/and the sealing system is nearly fully saturated, as a result to viscous deformation processes positive pore pressures cannot be avoided.
While there is extensive knowledge existing in Germany on long-term rock salt behavior (Wieczorek et al. (2010)) for the dry case (a), the material behavior of rock salt in contact with moisture/brine is only known qualitatively. What is missing here is a clear database coming from reproducible experimental investigations on the long-term recompaction behaviour of damaged rock salt itself and in interaction with the sealing system, featuring the presence of moisture/brine according to case (b) and (c).
In order to demonstrate hydro-mechanical material stability under representative load scenarios, the impact of the EDZ and the sealing capacity of the seal system, a comprehensive laboratory testing program is carried out.
The focus of the work is not on the observation of the saturation process and the derivation of 2-phase flow parameters, but on a systematic investigation of the material behavior leading to EDZ recompaction. It should result in a set of material parameters needed to treat the process in a (model theoretical) numerical way.
The rock salt samples for the experiments are taken from the vicinity of an existing dam that has been loaded in situ by the creeping rock salt for more than 10 years. Therefore, it is obvious that material properties, such as e.g. the initial gas permeability for the dry case, have to be measured under a load comparable to the in situ minimum stress.
Within this paper preliminary results from laboratory investigations on EDZ samples will be evaluated.

ARMA 15-0303

Geomechanis Issues Regarding Heat-Generating Waste Disposal in Salt

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With an abundance of scientific information in hand, what are the remaining geomechanics issues for a salt repository for heat-generating nuclear waste disposal? The context of this question pertains to the development of a license application, rather than an exploration of the entire breadth of salt research. The technical foundation supporting a licensed salt repository has been developed in the United States and Germany since the 1960s. Although the level of effort has been inconsistent and discontinuous over the years, site characterization activities, laboratory testing, field-scale experiments, and advanced computational capability provide information and tools required for a license application, should any nation make that policy decision. Ample scientific bases exist to develop a safety case in the event a site is identified and governing regulations promulgated. Some of the key remaining geomechanics issues pertain to application of advanced computational tools to the repository class of problems, refinement of constitutive models and their validation, reduction of uncertainty in a few areas, operational elements, and less tractable requirements that may arise from regulators and stakeholders. This realm of issues as they pertain to salt repositories is being addressed in various research, development and demonstration activities in the United States and Germany, including extensive collaborations. Many research areas such as constitutive models and performance of geotechnical barriers have industry applications beyond repositories. And, while esoteric salt-specific phenomenology and micromechanical processes remain of interest, they will not be reviewed here. The importance of addressing geomechanics issues and their associated prioritization are a matter of discussion, though the discriminating criterion for considerations in this paper is a demonstrable tie to the salt repository safety case.

Technical Session 19 – Elizabethan AB
Dams and Foundations

Tuesday, June 30, 2015, 08:00 am - 09:30 am

Chairs: Qiang Yang & Yaoru Liu

ARMA 15-0131

Long-term stability analysis for high arch dam based on time-dependent deformation reinforcement theory

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The project of high arch dam has an intense disturbance to its geological environment with high in-situ stress in the critical unstability state, and the creep and damage of foundation rock mass resulted from the process of non-equilibrium evolution has large influence on long-term safety of arch dam. Time-dependent deformation reinforcement theory (TDRT) has been presented for evaluating the long-term stability of arch dam, in which plastic complementary energy (PCE) is used to judge the steady stability or the viscoplastic flow of the structure, and the overstresses beyond the yield criterion are the driving force for non-equilibrium evolution of rock structures and the unbalanced forces are the required reinforcement forces. Based on Duvaut-Lions visco-plastic model and Lyapunov asymptotic stability analysis, the principle of minimum plastic complementary energy is proved for perfect and hardening yielding, in which viscoplastic structures deform tending to the limit steady state at which the PCE is minimized under time invariant loading and boundary conditions. So the PCE is a resonable and quantitative criterion for stability evolution and unbalanced forces can be used to determine the reinforcement since they have a complete mathematical basis. The expression of PCE and unbalanced forces for finite element method have been finished base on Drucker-Prager yield criteria. This theory is implemented in ***TFINE***, which is a parallel FEM code with GPU acceleration, and then used in the long-term safety evaluation of Jinping arch dam in China.
KEYWORDS: long-term stability, arch dam, time-dependent deformation reinforcement theory, plastic complementary energy, overstress

ARMA 15-0140

Clogging of drains and its influence on the stability of concrete dams

Jorge F. da Silva[1]
[1]CMEC

The paper discusses the various forms of drain clogging and its influence on seepage under concrete dams built on permeable rock foundations. The increment of the uplift pressure caused by reduction in drain length or diameter, or increase in roughness, is analyzed. The studies were based on a nonlinear numerical model developed for three dimensional seepage analyses. The importance of proper drain maintenance is stressed and a discussion on drain rehabilitation is presented.

ARMA 15-0164

Study on Weakening Effect of Structural Plane and Stability Analysis for Dam Abutment of Jinping High Arch Dam

Baoquan Yang[1], lin Zhang[1], yuan Chen[1], jianhua Dong[1], jianye Chen[1]
[1]*Sichuan University*

Abstract: The Jinping I high arch dam on the Yalong River, with 305m dam height, is the tallest dam of the world at present. At the dam site area, the geological conditions are complex, where exists faults, alteration veins, inner layer compressed zones, joint fissures and deep cracks and other kinds of weak structural planes. Besides, when the project put into operation, the strength parameters of these weak structural planes are easy to drop due to argillization, soften, humidifying and rheology under thousands of tons of water load and long-term effect of complexity seepage field. So the overall stability of the dam and foundation is a protuberant problem. In this paper, firstly, the weakening effect experimental research was carried out in order to study the weakening effect of weak rock and structural plane under the coupling interaction of stress field and seepage field after the impounding and operation of the project. The dam abutment rock samples of weak rocks and structural planes of Jinping I high arch dam were collected, and the similar specimens were prepared, then the triaxial compression tests and the water-rock coupling triaxial compression tests were conducted in the MTS815 Rock Mechanics Testing System. Through the tests, the weakening rates of weak rocks and structural planes were obtained, which provide the basis for determine the strength decreased range of weak structural plane in the global stability research of Jinping I arch dam. Secondly, in order to study the overall stability of the high arch dam under the condation of reinforcement foundation, the three-dimensional geomechanical model comprehensive method test has been carried out. In the experiment, the integrated strength decreased range of weak structural plane was determined as 30% according to the weakening test results, and in order to simulate weakening effect of rock mass and structural plane of dam abutment and dam foundation, the temperature analogous materials applicable to all types of weak structural plane strength weakening characteristics have been developed. Through the geomechanical model comprehensive method test, the deformation characters, the failure process, pattern and mechanism of dam rocks and structural planes in foundation and abutment are obtained. And the overall stability of comprehensive method test safety coefficient are determined as 5.2~6.0. Evaluation of the stability and security of the arch dam project has been done. The research results provide an important scientific basis for the design, construction and safe operation of the project.

Key words： Jinping high arch dam; weak rock and structural plane of dam foundation; weakening effect; the overall stability; temperature analogous material; the geomechanical model comprehensive method test

ARMA 15-0196

Impounding Deformation Analysis for Jointed Rock Slope Based on Generalized Effective Stress

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Abstract: Reservoir impoundment is a complicated problem in hydraulic engineering. It's related to different scientific phenomena in different scales, such as valley width contraction near the dam, slope deformation and stability in reservoir banks, and reservoir-induced earthquake in the basin-scale. Pore pressure increases as water level rises up, and causes material degradation and strength reduction in several ways. The effective stress law, which has been well developed and accepted, made a remarkable success in describing the mechanical behavior of saturated soil. However, rock masses are characterized by hydraulic conductive fissures and hardly permeable pores in solid matrix. The application the effective stress law is still limited in rock materials, especially when it comes to elasto-plastic constitutive relation. Conventional FEM calculation takes seepage as a constant load,

and applies pore pressure in the anti-slide stability analysis of slope. It's a two-dimensional application of effective stress law, which is capable of limit equilibrium state analysis rather than elasto-plastic deformation evaluation. This paper presents a unified effective stress law in elasto-plastic model for rock materials and applies it in the slope deformation assessment during reservoir impoundment. Moreover, Deformation Reinforcement Theory (DRT) is introduced in slope stability analysis with pore pressure considered, and the rigorous derivation is provided with Lyapunov stability and control theory. It proposes a feasible solution to determine the slope stability and failure mechanism. A case study is provided of the left bank slope of Jinping-I high arch dam. The results show that the Drucker-Prager criterion embedded with the concept of effective stress describes accurately the measured values of slope deformation.
Keywords: effective stress, jointed rock masses, slope deformation, reservoir impoundment, deformation reinforcement theory

ARMA 15-0616

Evaluating Foundation-Structure Behavior Using a Jointed Material Model

Joseph Kovacich[1], Richard Barrie[1], Luling Yang[2]
[1]MWH, [2]Langan

A two-dimensional finite element analysis was performed to evaluate the global stability of the desander structure and stilling basin wall for the 969 MW Neelum Jhelum Hydroelectric Project to understand complex foundation-structure interactions during the Design Basis Earthquake. The project is located in the state of Azad Jammu and Kashmir in Pakistan. The structures are founded on alternating layers of strong sandstone and siltstone and weak mudstone that dip steeply and, due to the proximity to the Main Boundary Thrust Fault, are highly deformed, disturbed, and sheared.
During excavation of the 150 meter long stilling basin, a 30 meter high and 60 meter wide rock slide occurred. Geologic mapping, kinematic, and back analysis indicated that sliding likely occurred along a combination of moderate dipping joints and bedding planes. Limit equilibrium methods were employed to redesign the slope, rock reinforcement, and pattern drain holes. However, the flattened slope undercuts the desander foundation. This necessitated backfill concrete and a thickened stilling basin wall to maintain the original finished project arrangement of the desander and to satisfy stability criteria.
Geologic mapping also identified a new potential failure mode, one that could affect global stability of the structure. Although sliding-type, and rock mass failure modes were considered in earlier analyses of the desander and stilling basin wall, shallow to moderate dipping discontinuities that cross-cut stronger sandstone layers could potentially link-up through the weak mudstone beds to form a weak, continuous interface. Thus, the elasto-plastic sandstone material model was modified to include a ubiquitous jointed material model. In addition, the redesigned slope geometry and the stilling basin wall concrete were incorporated.
Non-linear numerical analysis included the interaction of the foundation rock, stilling basin wall, desander structure partially supported on the stilling basin wall, adjacent massive conglomerate rock slope, and backfill. Modeling focused on seismic loading conditions with earthquake motions deconvolved at depth and radiation damping. Sensitivity evaluations of ubiquitous joint orientations, shear strength, and ground motion time histories were performed to understand foundation-structure behavior over a range of conditions. The models showed plastic strains in the mudstone and in limited areas of the sandstone, but a continuous, deep-seated sliding surface within the foundation was not identified. Stilling basin wall stresses and displacements are accommodated with a slightly deeper wall footing and reinforcing steel to satisfy structural stability criteria.

ARMA 15-0700

Experimental Evaluation of Rock Erosion in Spillway Channels

Michael George[1], Nicholas Sitar[1], Leonard Sklar[2]
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Removal of individual blocks of rock by hydraulic flows is one of the principal mechanisms by which scour of rock can occur. A series of flume experiments with different flow rates and block

configurations was carried out as a part of a comprehensive study of rock erosion in spillway channels of dams. In this paper we present the results of measured dynamic pressures and displacements for a 3D rock block obtained through physical hydraulic modeling testing at the University of California's Richmond Field Station (RFS). The results of the scale model experiments are analyzed using the block theory framework to assess its validity for prediction of 3D rock block erodibility.

Technical Session 20 – Elizabethan CD
Numerical Modeling - Mining

Tuesday, June 30, 2015, 08:00 am - 09:30 am

Chairs: Murali Gadde & Brijes Mishra

ARMA 15-0363

Numerical Simulation of Deformation and Failure Process of Coal-Mass

Khaled Mohamed[1], Berk Tulu[1], Ted Klemeti[1]
[1]*NIOSH - Office of Mine Safety & Health Research*

Rib-related accidents in underground coal mines continue to cause injuries and take lives at a rate of 1.3 fatalities per year for the last 17 years. Ultimately, rib safety will be brought about through an understanding of the causes and mechanisms that cause rib fatalities. Rational numerical simulation of coal-mass failure process is one approach to understand and mitigate the rib failures in underground coal mines.
Coal-mass is a coal structure, such as coal pillar, of smallest dimension larger than 1.5 m. The paper presents an approach for a coal-mass model that uses the constitutive relationships of Mohr-Coulomb model to describe the deformation and failure process of coal-mass. The strength parameters of the coal-mass model are estimated by the empirical failure and deformation criteria of rock-mass. The peak strength of the coal-mass is evaluated by the generalized Hoek-Brown failure criterion. The degraded stiffness and residual strength of the coal-mass model is estimated by Fang and Harrison local degradation model. The ductility of the coal-mass model is defined by Alejano and Alonso peak-dilation model.
The proposed model was implemented in a three-dimensional finite difference computer program (FLAC 3D) and tested numerically using published data acquired from a series of triaxial compression tests conducted on coal specimens of different sizes and large-scale in-situ compression tests conducted on coal pillars. The good agreement between the numerical models and both laboratory and in-situ results indicate that the proposed constitutive model can realistically represent the nonlinear behavior of coal material in both its brittle and ductile responses.

ARMA 15-0418

Underground Mine Roof Crack Formation Simulation with Creep of Rock Mass

Yuting Xue[1], Brijes Mishra[1]
[1]*West Virginia University*

Roof Fall Simulation with Creep of Rock Mass
According to MSHA, 265 miners were injured in roof and rib falls in 2013, down from 377 in 2012. Improvements in roof control technology have led to a significant decrease in accidents related to roof and rib falls, but such accidents are still a leading cause of injuries in underground coal mines. Numerical Simulation has been widely used to study its mechanism and preventions. Most of these works, however, were conducted without considering the time factor. In reality, the roof fall is a time-dependent failure process during which fractures initiate and propagate and finally lead to roof falls.
To investigate the time-dependent formation of roof falls, UDEC was adopted to simulate the time-dependent fracturing process with creep of rock mass. The rock mass around an opening was meshed as Voronoi blocks and the parameters for these blocks and boundaries were calibrated to make the boundaries as fictitious. The disturbed stress field, caused by excavation, would induce fractures

along these boundaries. After equilibrium, creep simulation was run to obtain the time-dependent fracturing process, which was induced by the creep of rock mass in this simulation. And the subcritical crack propagation was not considered. The simulation results showed that because of the stress difference around the opening, the creep of rock induced fractures in the mine roof with time, especially in the roof areas above the pillar edge. Then similar simulations were conducted with different vertical stresses, horizontal stresses, coal pillar stiffness and laminations to investigate their effect on the formation of roof falls with time.

ARMA 15-0423

Effect of Coal-Rock Interface Properties on

Kun Zhang[1], Eric Poeck[1], Ryan Garvey[1], Ugur Ozbay[1]
[1]*Colorado School of Mines*
Failure Stability of Coal Pillars Expressed in Energy Terms

Rockbursts, or coal bumps in coal mines, involve the spontaneous, violent fracture of rock. This paper discusses the application of energy concepts to back-analysis studies of coal bump events. Two-dimensional numerical models were constructed of coal pillars with a range of material properties assigned to both coal material and rock-coal interfaces. These models were used to explore the compounding effects of unstable failures in the coal and along the rock-interfaces. The results – reveal a potential de-confinement effect on initiating and sustaining coal bumps in large width-to-height ratio pillars, which offers a more complete understanding of the pillar behavior. Loading conditions applied to these models represent a pillar failing individually as well as a full panel collapses. Results from the pillar tests are presented in terms of the kinetic energy released as a consequence of unstable failure. Due to variation of coal and coal-rock interface properties, the magnitude of the excess kinetic energy was found to vary significantly. About 0.3% to 4.8% of the total energy applied to the system is found to be released as excess energy for the models used. The potential de-confinement within the coal-rock interface also plays an integral role in the failure of the coal pillar. This paper introduces a new methodology based on energy considerations to account for the effect of coal-rock interface properties on the failure stability of coal pillars.

ARMA 15-0552

Calibration of inelastic constitutive behaviour at a late stage mine and the challenges associated with data limited calibration

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A geomechanics study on the seismic risks associated with late stage mining at Morrison Mine was initiated in mid-2013. Recent large scale pillar extractions and increasing seismicity at the site identified the need to consider seismic risk as the mine extends deeper and sill pillars are thinned and removed. Due to an initial lack of available quantitative data, a 3D FDM elastic model was developed and the stresses conditions were qualitatively calibrated to the observed damage recorded throughout the mine during several field visits. An initial seismic risk review of the mine and the life of mine sequence was conducted using the calibrated model. Numerical predictions of ground response to mining have been a major input to rock burst risk mitigation strategies including the implementation of dynamic support, formulation of re-entry procedures and strategic mine sequencing.
With the installation of a mine-wide seismic array and strategically located borehole extensometers, as well as the regular measures of "depth of damage" during drilling, sufficient data was accumulated to sufficiently calibrate a plastic model of the mine. A transition from elastic to a plastic constitutive model provides more detailed assessment of the extent of yield, and the stress redistribution around yielded ground. The seismic risk review of the mine and the life of mine sequence was then re-assessed using the 3D plastic model. A comparison of the results of both the elastic and plastic model is presented within the paper and the apparent advantages and disadvantages of each method are also summarized.

KEYWORDS
Numerical modelling, case study, mine design, stress-induced damage, constitutive behaviour

ARMA 15-0679

Numerical Estimation of the Strength of St. Peter Sandstone Pillars- A Case Study at Iowa

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Estimation of pillar strength is a vital part of assessing the stability of pillars used in mines. Previous studies conducted to estimate the strength of St. Peter Sandstone pillars using empirical approach violated pillar design principles. As a result, the pillar strength formula postulated was unrealistic. In this study, numerical models using finite difference code will be used to predict the strength of St. Peter Sandstone pillars. The relevant input parameters will be discussed. Stress-strain behavior of the pillars acted upon by varying overburden loads are also presented. Based on the peak stress from the stress-strain plots, an empirical-based pillar strength formula is developed for St. Peter Sandstone. From this formula, a relationship has been established to define the maximum overburden depth for which a pillar will remain stable. In this investigation, a number of stable pillar cases used successfully in Iowa are also analyzed. The findings are expected to assist in effective room and pillar mine planning at St. Peter Sandstone Mine in Iowa.

ARMA 15-0855

APPLICATIONS OF FULLY HYDRO-MECHANICALLY COUPLED 3D MINE AND RESERVOIRE SCALE, DISCONTINUOUS, STRAIN-SOFTENING DILATANT MODELS WITH DAMAGE

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Hydro-mechanical phenomena for geotechnical extraction applications, as in the mining or gas and oil industries, are very important aspects of well stability, subsidence and in some cases, accurate forecasting of recovery. Most adverse rock related hydro-mechanical phenomena are stress path dependent. Uncoupled or loosely coupled modelling of flow or rock deformation is therefore not ideal; the important fluid rock coupling is over-simplified, or else, the stress path may not be replicated with high similitude. Here, we present a fully coupled, parallel solution formulation adopting single and multi-phase, multi-component fluid flow formulations into a discontinuum, strain softening, and dilatant Finite Element model. Particular emphasis is on the nonlinear coupling of the deformable and strain softening solid skeleton and the fluid phases, e.g. the change of hydraulic properties with evolution of damage in the matrix material as well as the effect of pore pressures on the overall stress distribution. This governing system of coupled nonlinear partial differential equations is embedded in the framework of a Finite-Element (FE) algorithm and applied to various large-scale real-life mine and reservoir models. The main benefit for practical reservoir engineering is that rock mechanics processes including damage, seismicity and deformation are likely to be better replicated with the fully coupled model than with part coupled or uncoupled models. This should enable more direct calibrationand potentially a closer replication of field observations for higher model reliability.
Keywords multi-phase flow, coupled geomechanics, discontinuities, strain-softening, large scale modelling, application, FEM[1]

ARMA 15-0572

An adaptive meshing approach to capture hydraulic fracturing

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Hydraulic fracturing is widely employed to stimulate oil and gas reservoirs to increase the productivity of these naturally fissured rock domains. Different numerical techniques are available to examine how hydraulic fractures propagate. They are mainly categorized into continuum and interface-based methods. Cohesive models are among the most effective class of interfacial approaches representing crack surfaces as sharp material interfaces. In lieu of a traditional cohesive model, we have formulated and employed an interfacial damage model that incorporates the processes of nucleation, growth and coalescence on the fracture surfaces. Utilizing a dynamic adaptive meshing, we employed a Spacetime Discontinuous Galerkin (SDG) finite element method to simulate hydraulic fracture propagation. Our SDG implementation adaptively aligns the element boundaries with crack-path trajectories that are obtained as a part of the solution according to a crack growth criterion. Thus, this model does not suffer the mesh-dependent effects encountered in most other numerical fracture models. Furthermore, no discontinuous features are introduced within the elements as opposed to XFEM and generalized finite element methods. Adaptive mesh refinement in an area allows free nucleation, growth and branching of cracks oriented arbitrarily in the domain without any mesh bias whereas a coarse mesh can be used in other regions of the domain to utilize an efficient implementation. Presenting numerical examples, we performed a sensitivity analysis of some input variables such as the magnitude of *in-situ* stress components, number and orientation of induced fractures is performed to demonstrate the effectiveness of our computational approach in resolving hydraulic fracturing.

ARMA 15-0293

Developing a Framework to Simulate the Hydraulic Fracturing of Tight Gas Reservoirs Based on Integrated Adaptive Remeshing & Combined Finite/Discrete Element Approach

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Developing a Framework to Simulate the Hydraulic Fracturing of Tight Gas Reservoirs Based on Integrated Adaptive Remeshing & Combined Finite/Discrete Element Approach

To improve the design of hydraulic fracture stimulations in tight gas reservoirs (TGRs) requires knowledge of the fracturing liquid flow within the fractures and matrix, the transport and deposition of proppant along the fractures, the evolution of the stress regime as the fracture propagates and the interaction of the propagating fracture with pre-existing natural fractures. All these aspects are interdependent, so it is challenging to evaluate the best practice for a specific hydraulic fracture stage. Several tools exist to predict the hydraulic fracturing process in TGRs. These tools range in complexity from simple analytical methods through to sophisticated numerical methods. Each has its benefits and drawbacks; many tools take a simplified approach and assume predefined fracture paths and aperture widths based on mass flow balance of the fracturing fluid.

Combined Finite Element (FE) and Discrete Element (DE) technology, such as the software package ELFEN (Rockfield Software Ltd), has been used in the past to predict the development of pressure driven fractures without the need to predefine or seed their direction or length. Current FE/DE technology relies on fractures following the element edges with a fine mesh in the region of the advancing fracture tip to adequately capture stress concentrations and subsequent damage of the

rock matrix. To capture the simulation of hydraulic fracture propagation in naturally fractured TGRs, where fractures may reach lengths in excess of 1km, this would necessitate a large number of elements to capture the fracture tip advancement.
The advancements outlined within this paper detail the integration of the fracturing FE/DE technology with advanced adaptive mesh refinement methods. This integrated technology enables the fracture prediction techniques of the FE/DE technology to be used to predict the growth of the fractures, in conjunction with local adaptive remeshing techniques, to insert the predicted fracture by updating the geometry and local mesh. The local adaptive procedure in which remeshing is only performed at the fracture tip significantly reduces the computational run-time when compared with traditional global remeshing procedures.
Another key aspect of the technology is the coupling between the flow of the fracturing liquid and the mechanical stresses in the TGR. The nonlinear fracturing liquid flow within the opening fracture is simulated using a zero thickness element which allows the longitudinal liquid velocity to vary according to a changing fracture aperture. The variation of the fracture aperture is dependent upon the stimulating fluid pressure, material properties of the TGR and the geometry of the fracture.
The performance of this newly developed technology is demonstrated via its application to conceptual models simulating the advancement of fracturing liquid driven fractures; sensitivities will include TGR in-situ stress regimes and its interaction with pre-existing natural fractures.

ARMA 15-0397

Numerical simulation of hydraulic fracturing using a three-dimensional fracture model coupled with an adaptive mesh fluid model

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In this paper, a three-dimensional fracture model (Guo et al., 2015) developed in the context of the combined finite-discrete element method is incorporated into a two-way fluid-solid coupling model (Viré et al., 2012). A methodology of using this new coupling model to simulate hydraulic fracturing problems is proposed. Particularly to solve the discrepancy problem in the coupling model between the continuous mesh used by the fluid code and the discontinuous mesh used by the solid code, a scheme to convert different meshes is developed, which establishes a relation between different meshes so that the variables can be transferred correctly.
A single fracture propagation driven by fluid pressures is simulated using the coupling model with the fracture model. The model first comes to an equilibrium state only under solid pressure conditions, which are designed to represent an *in situ* stress condition. Then fluids are injected into the pre-existing fracture from the left-hand side by a fluid pressure condition

ARMA 15-0507

Modeling the Interaction between Hydraulic and Natural Fractures using Dual-Lattice Discrete Element Method

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The interaction between hydraulic fractures (HF) and natural fractures (NF) will lead to the formation of complex fracture networks due to the branching and merging of natural and hydraulic fractures. Conventional methods with assumptions of homogeneous and continuous media are difficult to capture the realistic fracture pattern due to the pre-existing natural fractures. The natural discontinuities will alter the local principal stress orientation and pressure distribution when the hydraulic fractures are approaching natural fractures. Propagating multiple hydraulic fractures in naturally fractured reservoirs should carefully consider these complex interactions between hydraulic fractures and natural fractures.

A recently developed physics-based hydraulic fracturing simulator based on discrete element method is able to predict complex fracture networks generation in the presence of pre-existing natural fractures. By coupling geomechanics and reservoir flow within a dual lattice system, this simulator can effectively capture the poro-elastic effects and fluid leakoff into the formation. Fractures are explicitly represented by failure and removal of bonds between particles from the discrete element network, while the hydraulic conductivity is updated using the cubic law for laminar flow. This dual lattice DEM simulator can capture both tension-induced rock failure and shear-induced natural discontinuity opening.

Based on the model, we investigated the effects of injected fluid viscosity, the permeability of natural fractures, natural fracture toughness, in situ stress anisotropy and the fracture geometry on the interaction process. When HFs are intercepting single or multiple NFs, complex mechanisms such as direct crossing, arresting, dilating and branching can be accurately simulated. The results show that the low viscosity fluids leak more easily into the formation and are incorporated by NFs, resulting in enhancement of pre-existing NFs into more developed, complex networks. However, HFs will generally leap-frog the natural fractures with large viscosity injection inducing dominant, longer but narrower fractures patterns. With large initial permeabilities (close to the order of Darcy) in the NF, the fluid will easily penetrate into the natural fractures, and the hydraulic fracture maybe arrested at the intersecting point, opening the NF and possibly branching at the end of NFs. On the contrary, the natural fractures with small residual permeability (smaller than the order of milliDarcy) may not get enough inner pressure to drive the fractures open, and the HFs may directly across or branch at the intersecting point. The HFs are more likely to cross the discontinuity at larger approaching angle and large stress anisotropy. Accurate prediction of complex fracture networks generated provide a powerful tool for optimizing the fracture design and completion strategy in naturally fractured low-permeability reservoirs.

ARMA 15-0449

Investigation of Sequential and Simultaneous Well Completion in Horizontal Wells using a Non-planar, Fully Coupled Hydraulic Fracture Simulator

Ali Rezaei[1], Mehdi Rafiee[2], Mohamed Soliman[1], Stephen Morse[1]
[1]*Texas Tech University,* [2]*Statoil Gulf Services LLC*

Economical production of shale resources requires drilling horizontal wellbores with either sequential or zipper-frac completion in order to increase the fracture complexity in tight reservoirs. Properly estimating the final fracture geometry is the primary challenge in these complex fracturing practices. Various parameters control the fracture geometry including: fracture spacing, in-situ differential stress, pump rate and fluid viscosity. Two important fracture characteristic that should be addressed in such a complex system in order to have a proper estimation about fracture geometry, are fracture height growth and out of plane propagation. Although the modeling of hydraulically driven fractures in such a medium has been advanced over the past decades, there have been a few attempts to investigate these two phenomena together in an implicit model.

This article advances a hydraulic fracture model that predicts single and multi-fracture propagation. The model simultaneously simulates the dynamic growth of multiple fractures while addressing the interference between the fractures and its effect on fracture propagation.

The hydraulic fracture model uses a displacement discontinuity method for simulating fracture propagation in multi-fracture systems. Variations in the parameters affecting the behavior of hydraulic fractures were explored. The model can predict non-planar fracture propagation due to stress interference between adjacent fractures. Rock is considered homogeneous and linearly elastic. Fluid flow equations are solved using finite difference and are fully coupled with geomechanical solver. The effect on fracture propagation from variations in fluid viscosity, injection rate, stress interference, fracture spacing, stress anisotropy and perforation direction are presented for a multi fracture system.

The result of this study indicates that stress shadowing is the main factor affecting hydraulic fracture propagation. It changes the direction and magnitude of the principal stresses around fractures and may cause early screen out or tortuosity in fractures created from single or multiple wells. Therefore, an optimized fracture spacing is needed for placing more fracture into the system. The results of this study would help operators to better optimize the fracture spacing in horizontal wellbores and maximize the complexity needed for a typical horizontal fracturing job.

ARMA 15-0297

Incorporating viscous, toughness, and intermediate propagation regimes into enhanced pseudo-3D model

Egor Dontsov[1], Anthony Peirce[1]

[1] *University of British Columbia*

The design of a hydraulic fracturing treatment typically requires using a computational model that provides rapid results. One such possibility is to use so-called classical pseudo-3D (P3D) model with symmetric stress barriers. However, the original P3D model is unable to capture effects associated with fracture toughness in the lateral direction due to the assumption of a state of plane-strain (or local) elasticity in vertical cross-sections. On the other hand, an enhanced P3D model has recently been developed, which uses full elastic interactions and is capable of incorporating either toughness or viscous regimes of propagation by using the corresponding asymptotic solution at the tip element. However, hydraulic fractures typically transition from a viscous to a toughness propagation regime. Thus, if either a viscous or a toughness asymptote is used, the intermediate transition regime is not described accurately. To deal with this problem, this study aims to implement an intermediate asymptotic solution into an enhanced P3D model. To assess the level of accuracy, the results are compared to a reference solution that is calculated numerically using a fully planar hydraulic fracturing simulator (Implicit Level Set Algorithm (ILSA)). The ILSA model also incorporates the intermediate asymptotic solution for tip elements that capture the transition from viscous to toughness regimes.

Technical Session 22 – California East
Salt Rock Mechanics

Tuesday, June 30, 2015, 11:00 am - 12:30 pm

Chair: Chloe Arson

ARMA 15-0517

Gas flow measurements through consolidating crushed salt

Stephen Bauer[1], John Stormont[2], Scott Broome[1], Brandon Lampe[2], Melissa Mills[2], Frank Hansen[1]

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This work represents a portion of a study supported by the Nuclear Energy University Partnership (NEUP) which intends to provide data and analyses to evaluate the long-term integrity of consolidated backfill barriers of natural salt to eventually predict the long-term thermal-hydraulic-mechanical response of a generic salt repository for high-level nuclear waste disposal. Rock salt has been considered as a potential disposal medium, because of its low susceptibility to flow of water and gas, its very low porosity and its ability to creep and heal fractures induced during excavation through emplacement time periods. The backfill of interest in this study is blown-in “crushed salt", which is obtained from mining operations by mechanical processes using, for example, a road header. After waste emplacement and backfilling, the natural salt host rock creeps under the effect of temperature and ambient stress conditions. As a result, the backfill will reconsolidate progressively. Determination of the thermal-hydraulic-mechanical constitutive properties, their inter-relationships, and operative deformation mechanisms of consolidating crushed salt are objectives of the NEUP study.

Here we report on an initial phase of the work in which an experimental program is developed to measure gas flow through consolidating crushed salt. The fluid flow measurement system is designed and assembled to "flow through" samples undergoing hydrostatic and/or shear stress conditions at elevated temperature and pressure (i.e. Broome et al, 2014). For anticipated high flow rate conditions (high porosity), gas flow is measured using a constant head (or pressure) technique and inert gas as the permeant. For anticipated low flow rate conditions, (low porosity) gas flow is measured using a technique in which a helium mass spectrometer is used to detect flow. In these techniques, the test specimen is placed between two metal platens having central ports that permit the permeant (helium) to enter and exit the specimen. Highly-permeable porous felt metal disks are placed in the interface between the platens and specimen to distribute the helium pressure across the full cross-section of the specimen. The specimen dimensions are tracked with internal sample displacement gages during deformation; these measurements are critical to assessing permeability. Gas flow is measured at specific reconsolidated states.

Experimental conditions of interest in our study are temperatures ranging from lab ambient to 250C, dry crushed salt, and dry crushed salt with specified weight percent water added, porosities initiating at ~40 percent and decreasing to values representative of intact salt, and hydrostatic and deviatoric stress conditions consistent with excavations and ultimate closure of a potential salt repository at approximately 700 meters in depth.

Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-4AL85000.

ARMA 15-0698

Healing of Rock Salt Damage and Applications

Christoph Lüdeling[1], Ralf Günther[1], Markus Knauth[1], Wolfgang Minkley[1]

[1]*IfG*

Under high deviatoric stresses, rock salt shows shear failure, accompanied by softening. Microscopically, softening results from the generation and accumulation of microcracks, and is consequently associated with volume increase, i.e. dilatancy. Besides mechanically weakening the rock, dilatancy also implies porosity and might thus lead to fluid permeability of the usually impermeable salt rocks. On the other hand, dilatancy is directly accessible in the laboratory. Hence, dilatancy can be considered as a convenient indicator for microscopic damage, and is used in various constitutive models and their numerical implementations.

On the other hand, it is well-known that rock salt can heal itself: Cracks can close due to viscous creep, and cohesion is restored by physicochemical processes on contact surfaces, such that over time, the damage induced by shear failure is completely healed in suitable stress conditions. This implies that softening, and the associated dilatancy, should decrease to zero.

The IfG has developed a phenomenological model which the model treats healing as a creep-like, i.e.\ viscous, process with two components,

d(dilatancy)/dt

The first term dominates for large dilatancy values (corresponding to the post-failure range), where the material containing open cracks, while the second term is more important at lower dilatancy, where new cohesion is developed on closed crack surfaces.

This healing model has been included in the two salt rock constitutive models developed by the IfG, the advanced strain-hardening model of Günther and Salzer and the elasto-visco-plastic model of Minkley. Numerically, healing is implemented in the numerical codes UDEC, 3DEC, FLAC and FLAC3D, and validated on laboratory experiments. In the paper, we discuss the healing model in detail and present results of the numerical analyses, as well as some geotechnical applications.

Healing was the focus of a joint project of various German and US institutions, and we briefly discuss the overall picture.

ARMA 15-0026

Numerical modelling of salt leaching-dissolution process

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The exploitation or extraction of salt by leaching process is used intensively nowadays. This solution mining is a well known method for extracting salt by dissolving this mineral with water. In this analysis about cavity dissolution modeling, we consider the case of a binary system, i.e., a chemical solute corresponding to the solid that is dissolved by a "solvent" (mainly water). Rock salt dissolution is controlled by thermodynamic equilibrium at the interface, i.e., equality of the chemical potentials. In this paper, a local non-equilibrium Diffuse Interface Model (DIM) and an explicit treatment of the brine-salt interface (using an ALE (Arbitrary Lagrangian-Eulerian) technique) are introduced in order to solve dissolution problems in such binary cases. The control equations are obtained by upscaling micro-scale balance equations for a solid-liquid dissolution problem using a volume averaging theory. This results in a diffuse DIM model for dissolution. Based on this mathematical formulation, dissolution test cases are presented. We introduce and discuss the main features of the method. An optimum expression for the solid-liquid exchange coefficient is obtained by comparison with reference solutions obtained by ALE simulations. Illustrations of the interaction between natural convection and forced convection in dissolution problems are presented. The ability of the method to track accurately the time and space evolution of the rock salt-fluid interface is shown through several examples. The method is applied at the reservoir scale and a comparison with experimental monitoring is performed.

ARMA 15-0087

Fabric-enriched Modeling of Anisotropic Healing induced by Diffusion in Granular Salt

Cheng Zhu[1], Chloe Arson[1]
[1]Georgia Institute of Technology

Because of its low permeability and favorable creep properties, salt rock is envisioned as a possible host medium for geological storage facilities, such as nuclear waste disposals, oil or gas storage facilities, geothermal systems, and more recently compressed air energy storage facilities. Diffusive mass transfer in salt rock induces creep strain and also accelerates crack healing through local transfer of mass. The same creep properties that can induce crack healing under high pressure and temperature can also result in local stress concentrations and consequent micro-crack dilatancy. To understand and predict microscopic mechanisms at the origin of damage and healing, we propose a fabric-based thermo-mechanical model coupling anisotropic damage and healing processes around salt caverns.
We extend our previous thermodynamic framework for thermo-mechanical crack opening, closure, and rebonding (Zhu and Arson, 2014) to anisotropic healing processes. The free energy of a representative element volume is expressed in the form of a polynomial comprising a purely thermo-elastic potential, a damage propagation dissipation potential, and a diffusive mass transfer dissipation potential. We account for the compression strength recovery induced by normal crack closure by introducing a unilateral condition in the stiffness model. In order to track the evolution of voids between salt crystals with lower load levels but higher healing rates than what is practically encountered in underground storage, we carry out creep loading tests on table salt. We used different loading conditions and inclusion materials to study the potential recurrence of topological patterns at grain boundaries. We develop an image post-processing methodology to track the packing and relative arrangement of the grains and voids, and we define fabric descriptors that can be correlated

with alternative damage and healing tensors in thermodynamic models. Fabric tensors conjugate to force and flux variables that are involved in three-dimensional diffusion equations.
We calibrate the new constitutive model against experimental data published on salt, and simulate damage and healing under uniaxial loading conditions at the material point (with MATLAB). We propose a Finite Element Analysis of a few salt caverns used for geological storage, in Europe and Northern America. To this aim, we implement the new damage and healing model in POROFIS Finite Element program (Pouya, 2014). Simulations illustrate the effects of anisotropic damage, healing duration, and healing temperature on the stress distribution and deformation within the Excavation Damaged Zone around the cavern. We expect that our modeling approach will advance the fundamental understanding of damage and healing processes in salt at both microscopic and macroscopic levels, and to assess long-term behavior of geological storage facilities.

Keywords: salt rock, continuum damage mechanics, healing, image analysis, excavation damaged zone, finite element analysis

ARMA 15-0440

Long-term modeling of coupled processes in a generic salt repository for heat-generating nuclear waste: preliminary analysis of the impacts of halite dissolution and precipitation

Laura Blanco Martin[1], Jonny Rutqvist[1], Jens T. Birkholzer[1], Alfredo Battistelli[2]
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Rock salt is a potential medium for the underground disposal of nuclear waste because it has several assets, in particular its ability to creep and heal fractures and its water and gas tightness in the undisturbed state. In this research, we focus on disposal of heat-generating nuclear waste (such as spent fuel) and we consider a generic salt repository with in-drift emplacement of waste packages and subsequent backfill of the drifts with run-of-mine crushed salt. As the natural salt creeps, the crushed salt backfill gets progressively compacted and an engineered barrier system is subsequently created.
The safety requirements for such a repository impose that long time scales be considered, during which the integrity of the natural and engineered barriers have to be demonstrated. In order to evaluate this long-term integrity, we perform numerical modeling based on state-of-the-art knowledge. In the present work, we analyze the impacts of salt (halite) dissolution and precipitation within the backfill and the host rock. For this purpose, we use an enhanced equation-of-state module of TOUGH2 that properly accounts for temperature-dependent solubility constraints. We perform coupled thermal-hydraulic-mechanical modeling and we investigate the influence of the mentioned impacts. The TOUGH-FLAC simulator, adapted for large strains and creep, is used. Currently, the thermal-hydraulic properties of brine and halite are accounted for more realistically than in previous investigations.
In order to quantify the importance of salt dissolution and precipitation on the effective porosity, permeability, pore pressure, temperature and stress field, we compare numerical results that include or disregard fluids of variable salinity. The sensitivity of the results to some parameters, such as the initial conditions in the host rock, is addressed as well.

ARMA 15-0619

Dimensioning principles in potash and salt mining to achieve stability and integrity

Wolfgang Minkley[1], Jan Mühlbauer[1], Christoph Lüdeling[1]
[1]IfG

For a long time, the dimensioning of underground openings in salt rocks was based primarily on mining experience. Only in the last century, analytical and numerical calculation methods of geomechanics have been increasingly used. This was not least due to some catastrophic collapses of mining fields (rock bursts) with a strong mining-induced energy release and the loss of potash and rock salt mines by flooding. Both practical experience and geomechanical calculations are essential for an economical and sustainable salt extraction at high recovery rates and are complementary to each other.

The fundamental requirements of safe dimensioning for potash or rock salt mining are the guarantee of stability of the mining system integrity and protection of the hydraulic protection layers or geological barriers.

For the collapse of mining fields, insufficient dimensioning of the pillars and the brittle fracture behavior of the mined rock salt played crucial roles. The tendency of brittle fracture behavior decreases in the order from carnallite, hard salt, trona, sylvite to halite. Therefore, rock bursts occurred primarily in potash mines where carnallitite was mined. In sylvite and rock salt mines only a few rock bursts are known worldwide, and only if extremely high recovery rates and, accordingly, very slender pillars were realized. The analysis of in-situ collapses provides a basis to check dimensioning approaches and to derive empirical relationships for the necessary ratio of pillar width to pillar height (slenderness ratio) required to ensure the viability and stability of pillars in salt rock.

In addition, geomechanical calculations based on suitable material laws are required to quantitatively assess the system stability and integrity at the specific geological conditions. The material laws must be able to properly capture the spectrum of mechanical properties of salt rocks and discontinuities, ranging from visco-plastic deformation with time-dependent softening to extremely brittle fracture. With increasing extraction rate the convergence-induced stresses in the mining horizon are increasing in the surrounding geological barriers, from room and pillar mining to complete longwall caving. To maintain the integrity and tightness of the hydraulic protection layers, the tensile stress criterion, the shear stress criterion (dilatancy criterion) and the minimum stress criterion (frac criterion), have to be satisfied.

Due to violation of the tensile and shear stress criterion, cracks arise mainly in the near field of the mining horizon. The minimum stress criterion also acts in the far field, due to the mining-induced extensive and far-reaching stress redistribution.

So-called hard mining edges have repeatedly led to the flooding of salt mines, because directly above mining edges shear stresses are concentrated and, at the same time in greater distances, extensional stresses are induced which result in a drop of the minimum principal stress at the top of the protective layer (top of the saliferous formation), until the minimal stress becomes lower than the acting groundwater pressure, at which point water starts to penetrate into the barrier.

The mining dimensioning has to be designed in that way that the integrity criteria are fulfilled in a sufficiently thick saliferous protective layer (> several tens of meters). For a loss of integrity, it is sufficient that one of the criteria is violated. The minimum stress criterion is of particular importance because in case it is violated, a fluid pressure-driven percolation perpendicular to the smallest principal stress, i.e. in the direction of the major principal stress, begins. This was repeatedly responsible in the past for the flooding of potash and rock salt mines causing, in extreme cases, sinkholes at the surface.

In coupled mechanical-hydraulic models the interaction between mining dimensioning and its effect on the surrounding hydraulic protective layers can be analyzed quantitatively.

In the article the geomechanical principles for dimensioning of static and dynamic stable mining fields and for maintaining the integrity and tightness of the hydraulic protection layers during recovery of potash and rock salt deposits are presented and discussed.

Technical Session 23 – Elizabethan AB
Modeling of Fractured Media

Tuesday, June 30, 2015, 11:00 am - 12:30 pm

Chairs: Yossef Hatzor & Genghua Shi

ARMA 15-0829

Analysis of dam abutment erosion by overtopping water using DDA

Ruidong Peng[1], Man-chu Yeung[2], Chin Man Mok[3], Engsew Aw[4], Tao Yeung[5], Robert Wright[6]

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The potencial and extent of rock erosion due to plunging water jets from dam overtopping need to be investigated for many existing dams. Hydraulic scour has been observed in some dam spillways and may cause downstream erosion. Methods to assess the effects of spillway erosion have received considerable attention in the past few decades. Common methods have been developed based on empirical data. Numerical simulation based on the Discontinuous Deformation Analysis (DDA) is used in this study to allow a mechanics-based assessment that takes into account the specific geologic conditions. In the case with plunge pool presence, conventional DDA models are improved to allow the input of time-dependent loads that might depend on joint apertures. The modified DDA program is tested using an idealized example simplified based on existing dam. The results show that rock erosion is affected by duration and intensity of the water jet hitting the rock. Some failure phenomena are observed for some cases analyzed. The purpose of this paper is to present the DDA model that incorporates preliminary hydro-mechanical coupling effects and to present results of analyses using this DDA model. A similar study based on discrete element method using the computer code UDEC is discussed in a companion paper and their results will be compared.

ARMA 15-0636

Modeling Hydraulic Fracturing in Naturally Fractured Reservoirs Using the Discontinuous Deformation Analysis

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In the field, many natural gas reservoirs are characterized by large networks of pre-existing natural fractures. When these reservoirs are hydraulically fractured, these networks can greatly impact both the geometry of the propagating hydraulic fractures and the production properties of the overall reservoir. To characterize hydraulic fracturing in these systems, models are needed that can account for the complex interaction of hydraulic fractures with pre-existing natural fracture networks. In this work, a method is presented for modeling hydraulic fracturing in reservoirs with pre-existing fracture networks using the Discontinuous Deformation Analysis (DDA). The method is based on previously published studies that developed and validated a fully implicit algorithm for coupling the DDA to a discrete fracture network model for fluid flow. As part of this work, an algorithm is introduced for modeling pre-existing fracture networks in the DDA. Fractures are generated using probability distributions for the length and density of a fracture system and are assigned to joints between DDA mesh elements based on the joints' azimuth. Using this method, hydraulic fracturing is simulated in various hypothetical reservoirs subjected to different levels of background stress. In addition to displaying the ability of the method to model hydraulic fracturing in naturally fractured reservoirs, the results of this work demonstrate that principal stress will be one of the primary factors determining the direction of fracture propagation within a naturally fractured system. Pre-existing fracture networks, however, are also seen to influence the direction of fracture propagation, particularly when the difference between the maximum and minimum principal stress is minimal. Finally, the results demonstrate that fluid viscosity and injection rate will have a direct impact on the

extent to which fracturing fluid will invade a pre-existing network of natural fractures, but only a minimal impact on the direction taken by propagating hydraulic fractures.

ARMA 15-0542

Effect of Fracture Dilation Angle on Stress-Dependent Permeability Tensor of Fractured Rock

Kiarash Farahmand[1], Alireza Baghbanan[2], Kourosh Shahriar[3], Mark Stephan Diederichs[1]
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Fluid flow in fractured rock is controlled by flow paths in a network of discrete pre-existing fractures. The same can be said for fracture networks induced by loading or unloading. In both cases, or in the combined case, the determination or evolving modification of an equivalent permeability tensor is necessary for up-scaling the equivalent continuum hydro-mechanical properties of a fractured rock. The evolution of fracture aperture during shearing and the associated dilation process control the permeability of single fractures and fracture networks. In order to understand this process, a number of rotated Discrete Fracture Networks is generated with different mean fracture orientations. Permeability tensors are calculated, from distinct element hydro-mechanically coupled models, when initial fracture apertures are correlated with fracture trace length in 2D models at different stress ratios. A non-linear behavior between normal stress-normal displacements of fractures is adopted so that both scale and stress-dependent normal stiffness of the fractures can be considered. The results show that overall permeability continued to decrease, with the increase of stress ratio, when zero dilation is assigned to the fractures. However, when the dilation mechanism of the fractures is modeled, equivalent permeability decreases with increasing stress magnitudes when stress ratio is not large enough to initiate shear dilation processes in a fracture. In this case, normal closure of the fractures is the dominating mechanism for decreasing the overall permeability of models. When stress ratios increased up to k=3 or higher, most of the fractures will experience shear dilation with increasing overall flow rates of models. Flow rate distribution at different stress ratios show that a small number of large fractures with large initial aperture values remains conductive in all stress conditions and control the permeability and flow pattern of the models significantly. With increasing stress ratios, it becomes more and more difficult to establish an equivalent permeability tensor, compared with the non-stressed model. For models with non-zero values of fracture dilation angle, the existence of permeability tensor is not affected by changing in the magnitude of dilation angle when small stress ratio is applied. However, when stress ratio increases up to k=3 or higher, the values of dilation angles lead to additional contributions from shear dilations of fractures which become the main reason for increasing of permeability, compared to the models with lower dilation angle.

Keywords: Stress ratio; Dilation angle; Equivalent permeability tensor; Aperture–Trace length correlation; Discrete fracture network; Discrete element method

ARMA 15-0710

Numerical modeling of crack propagation mechanism in jointed rock slopes using indirect BEM and DEM

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The large-scale failures of the geo-structures may be caused by the crack propagation and coalescence of the main discontinuities in jointed rock masses.Although the conventional rock mechanicsprovides the useful means to investigate the failure types and its area, it seems that typically complex failure may be governed by progressive and brittle fracture .In this paper, linear elastic fracture mechanics principleis widely applied for the analysis of fracture problem in discontinuous rock slopes. In particular, a numerical modeling based on the undirected BEM technique of the higher order displacement discontinuity method (HODDM) presents the trajectory of stable and unstable fracture growth. Fracture parameters such as stress intensity factors (KI, KII, and KI-II) resulting from the criterion of maximum tangential stress can determine the formation of

step-path failure surface in typical rock slopes including pre-existing single cracks and discrete joint sets. Finally, the estimation of normal and shear stresses adjacent to the crack tipcan be applied in Mor-Coulomb's criterion to determine safety factor and the different failure paths and the whole critical failure surface.

Keywords: critical failure surface, discontinuous rock slopes, progressive step-path fracture mechanism, undirected boundary element method

ARMA 15-0084

Coupling of rupture growth and fluid flow along a shear fracture containing structural complexities

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Injection of liquid waste has been observed to result in generation of seismic events and some of these may be large enough to be felt at the surface. There seems to be a correlation between the volume injected and the size of the seismic events generated (Rutledge, et al., 2004). Therefore, the aperture distribution along the fracture path, including the initial and subsequent propagation path, becomes very important. However, the mechanics of the induced seismic events are a topic of ongoing research. An integrated coupled hydraulic fracture model should be applied to this problem to predict the relationship among stress, pressure and rupture growth. In this paper, we will investigate rupture growth in fractures that are not simply planar by including three kinds of pre-existing structural complexities, namely in-plane large aperture segments, out-of-plane offsets and fracture branches, using a boundary element model (Zhang et al., 2009). The effect of these features on fluid pressure and flow in the fracture is studied for conditions that produce growth mainly in shear mode after shear stress overcomes the along-fracture frictional stress. The slip reactivation and resulting rupture growth is driven by fluid injection into a shear fracture and is potentially associated with seismic events.

In our numerical model, the rock mass is assumed to be impermeable and isotropic elastic and the Newtonian fluid flow obeys the Reynolds equation. The frictional strength, which obeys the Coulomb frictional law, is affected by the fluid pressure, which acts to reduce the effective normal stress. Numerical results based on a coupled rock deformation and fluid flow modelling are provided for pressure and aperture variations with time and location, with an aim to better understand the rupture growth behaviour associated with fluid injection.

In the presence of large aperture fracture segments on a fault as shown in Fig.1, fluid flow toward the fracture tip is accelerated locally, but the pressure increase is limited. Rupture growth in shear mode can occur at a pressure less than the confining stress, especially when the fault is critically loaded. Under the normal effective stress cycles generated by the seismic wave of a large remote earthquakes or through fracture interaction (Ellsworth, 2013 and van der Elst, et al., 2013), the rupture growth occurs in a sporadic manner, similar to stick-slip motion, at a frequency depending on the cyclic pressure and fluid viscosity. See Fig. 2 which shows episodic growth under different stress cycles and for different fluid viscosities. Fracture growth leaves behind the post-failure fracture path that is filled with fluid from the injection point.

The out-of-plane offsets play a role in connecting two fracture steps. The displacement transfer between the steps and offsets has been discussed by Daneshy (2004) and Jeffrey et al. (2009) and affects the fracture aperture. The suction and injection volume exchange action at the dilatational offsets that occurs as they open and close, tends to drive episodes of shear rupture growth, independent of the applied shear stress direction.

Locations of fracture branching form a triple junction. The reactivated slip along the branches is always accompanied by fracture opening. This can alter the fluid flow direction. The branch acts as a valve in adjusting the flux into the downstream segment along the rupture. Multiple finite branches can divide the rupture into a few compartments, each of which has its own flow characteristics.

ARMA 15-0585

3D Simulation of Multiple Fracture Propagation from Horizontal Wells

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[1]*University of Oklahoma*

The paper presents three-dimensional numerical analysis of multiple fracture propagation from the horizontal wells. A three-dimensional numerical model is developed using a combination of the finite element method, the indirect boundary element method, and the linear elastic fracture mechanics. The reservoir rock mass is assumed homogenous, isotropic, and linear elastic. The fracture fluid flow is assumed laminar flow and the fracturing fluid shows Newtonian behavior. The fracture fluid flow is analyzed following the Galerkin's finite element approach, the rock mass deformation is analyzed using elastic displacement discontinuity method, and the crack tip displacement approach is used for the mixed-mode fracture propagation. Details of mathematical formulations and methodology for numerical implementation are presented first. Then, the model is validated with some known analytical solutions for specific cases. Finally, several cases of planar and non-planar multiple fracture propagation in case of sequential and simultaneous fracturing for the Niobrara Chalk formation are analyzed. Some special mechanisms such as fracture link-up and interaction between the hydraulic fractures and the natural fractures are considered. The results demonstrate that along with the rock and fluid properties, the stresses shadowing effect which mainly depends on the spatial interval between the fractures plays a critical role in the multiple fracture propagation.

Keywords: Multiple fracture propagation, sequential and simultaneous fracturing, stress shadowing, fracture link-up, fracture interaction

Technical Session 24 – Elizabethan CD
Hard Rock Ground Control and Rock Slopes

Tuesday, June 30, 2015, 11:00 am - 12:30 pm

Chairs: Gabriel Esterhuizen & Zara Hosseini

ARMA 15-0221

A new method to measure tri-axial static strain change based on relative displacements between points for open pit slopes

Dale Preece[1], Ruilin Yang[1]

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All rock excavations by means of natural gravity caving, mechanical excavation or blasting cause redistribution of the static stress and strain in the remaining rock mass. It is critical to measure the change of the strain state. Such a measurement can serve as quantification of the damage and of effectiveness of the blast design or excavation methods in terms of minimized disturbance to the remaining rock mass.

Surveying fixed markers (e.g. posts on a highwall) on slopes or rock structure has been used to monitor the displacement of a slope or rock structure. New technologies developed over the last few decades; such as GPS, radar systems, three dimensional photogrammetry and multi-sensor displacement monitoring, are also used nowadays to monitor displacement. However, such monitoring does not provide the changes in the three dimensional strain tensor of the slope or highwall. Instead the analysis only gives displacement change at separated monitoring spots. In general, the strain in a slope may be a more direct indicator of the slope stability than discrete displacements.

This paper presents a method for measuring the change of the static strain state at a remaining rock mass or ground associated with operations of excavations, such as blasts, mechanical means or gravitational caving of a portion of a ground. The method based on measuring coordinates of

selected points with recent accurate survey techniques before and after an excavation. The paper also shows that for small deformation the reference point for survey before and after an excavation does not need to be the same.

The calculation of the strain change is from solving a set of simultaneous equations for the displacement gradients. With the number of survey points larger than the minimum number required, the number of the independent equations is greater than the number of unknowns to obtain the least-square solution in order to minimize the measurement errors.

ARMA 15-0501

A review of pillar design for platinum mining to enhance stability: A Zimbabwean case study

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Any bord and pillar platinum mine thrives on effective design of pillars. Pillars have to be large enough to ensure safety and small enough to ensure economic and sustainable exploitation of the mineral resource. Consideration of span of the bords of the working area is also crucial to safe and economic design of the mining layout. This research makes a critical review of the current design approach so as to understand the contributors to pillar failure in a section of an underground platinum bord and pillar mine. The research focuses on the areas that have been plagued by bad ground and seeks to determine the suitability of the current design in such conditions with an objective to redesign the section so as to curb the consequences of pillar failure in the operation.
At the core of this research is the detailed geotechnical data of the area that was studied. Making use of Rock Mass Classification (RMC) and other rock engineering techniques, the review indicates that the adopted design is ill-suited for the ground conditions evaluated thus confirming the problem's origin. The safety factor analysis shows that the ground conditions in the area of study would pose a greater risk due to failure of pillars. The conditions, predominantly the closer joint spacing made the rock mass deteriorate in strength and quality thus the pillar size needed to be increased so as to maintain the required strength. This shows that the pillars in the study area are at a higher risk of failure hence motivating for the redesign process. This paper details the proposed redesign which, if implemented, will see a reduced extraction ratio but will enhance stability and facilitate for optimum mining operations to be carried out at the mine.

ARMA 15-0510

Numerical Simulation of End Constraint Effect on Post-peak Behaviors of Rocks in Uniaxial Compression

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Efforts had been made by many researchers to study the mechanical and geometrical factors that influence peak strength of rocks, but few investigations, experimentally or numerically, focused on the influences of loading conditions on the post-peak behavior of rocks. In this study, numerical simulations of uniaxial compression tests were carried out to investigate the combined influences of end constraint, platen stiffness, and specimen geometry on the post-peak behaviors of brittle rocks. First, simulation of the effect of end constraint at specimen-platen contacts was conducted using cylinder specimens with a height to diameter ratio (H/D) of two. The modeling results indicated that friction in the tangential direction of the contacts resulted in a negligible increase of the peak strength of the rocks, but more ductile responses of the rocks in the post-peak region were observed. In addition, there was no influence of the loading platen stiffness applied normal to the contacts on the peak strength of the rocks, whereas the post-peak stiffness of the specimens was enhanced with a stiffer loading platen.

Next, the influence of specimen geometry on the post-peak behavior of rocks also was investigated. The effect of contact friction on the post-peak behavior of rocks became more evident with the

decrease of specimen slenderness starting from H/D = 2. In addition to cylinder specimens, prim shaped specimens were also loaded in uniaxial compression. It is found that the peak strength was not affected by the shape of the specimens. Similar post-peak behaviors were also observed for both the cylinder and the prism specimens under the same end constraint.

We found from this study that the effect of loading stiffness on the post-peak stiffness of rocks also depended on the specimen geometry. It was observed from the simulation that a uniform stress state under ideal axial loading was disturbed by the end constraint, and the stress distribution was further affected by the specimen geometry. For varied slenderness of the specimen, the amount of confined zones near the end surfaces affected rock failures, from spalling (H/D =0.5), hour-glassing (H/D =1 and 1.5), to shear failures (H/D ≥2).

It was found from this study that the post-peak behaviors of rocks depend on the end constraint, loading stiffness, and specimen geometry. Thus, the loading conditions in rock testing should be considered for calibrating of the strain-softening model parameters of brittle rocks. Furthermore, in order to assess the real rock properties accurately, it is preferable to minimize the influence of end constraint so as to achieve uniform loading. A modified layout of specimen-spacer-platen loading scheme in a rock test was proposed in the end.

Key words: friction; loading stiffness; specimen geometry; post-peak; uniaxial compression

ARMA 15-0714
Development of Cuttability Chart for a Limestone Cutting with Monowire Cutting Machine

Emre Yilmazkaya[1], Yilmaz Ozcelik[1]

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Monowire block cutting machines can be used for natural stone block squaring operations and slab cutting operations from natural stone blocks. The plants where the cutting operations are performed demand high product quality with minimum operational costs. The purpose of this study is to develop cuttability chart for Burdur Dark Beige White limestone sample based on unit wear and unit energy in monowire cutting system and also perform cutting optimization. For this purpose, the full automatically servo controlled monowire cutting system which can cut blocks in three dimensions were developed in Hacettepe University Mining Engineering Department. Cutting experiments were performed at different wire rotation speed (peripheral speed) and wire downward movement speed (cutting speed) on the limestone block which is transported to the laboratory. A cuttability abacus in monowire cutting system taking into consideration the unit energy consumption during cutting operation and unit wear on diamond beads was developed with Design Expert 7.1 software for Burdur Dark Beige real marble sample by using the results obtained.

ARMA 15-0793
Deterministic and Probabilistic Block Theory Analyses Comparison for an Open Pit Mine Rock Slope in USA

Pinnaduwa Kulatilake[1]

[1]University of Arizona

The ultimate slopes of an open pit mine are generally excavated to the steepest possible angle because the economic consequences of the excavation angle are significant. For large scale open pits, changes in slope angle by approximately 2–3 degrees may correspond to hundreds of millions of dollars in project value. However, steeper slope angles result in an increased probability of slope failure. Therefore, it is critical to calculate the maximum safe slope angles (MSSA) and also to estimate probabilities of slope failure with respect to different cut slope dip angles. The block theory is a very useful technique to investigate possible failure modes of rock blocks and to determine MSSA for rock slopes. The block theory considers block formation by discontinuity planes along

with a cut slope, without assuming presence of lateral release planes as in kinematic analysis. Therefore, the results obtained from the block theory analysis can be considered to be closer to the reality than that coming from kinematic analysis. However, block theory is usually used to perform deterministic analysis using single fixed values (typically mean values) to represent orientation of discontinuity sets and strength parameters. The open pit mine slope stability is one of the mining subjects dominated by variability and uncertainty because the slopes are composed of natural heterogeneous materials containing many discontinuities. In discontinuous hard rock masses, the variability and uncertainty of rock slope stability analyses mainly arise from discontinuity geometry and strength. Therefore, it is important to incorporate the said variability and uncertainty in performing block theory analysis.

The objective of the study was to develop a new formulation to conduct a probabilistic block theory analysis and to apply that technique to perform a case study for a part of an open pit mine and to compare the results obtained between deterministic and probabilistic block theory analyses.

The slope had two major rock formations: (a) DRC rocks and (b) DP rocks. Needed geological and geotechnical data for the analyses were obtained from field and laboratory investigations. Discontinuity orientation data were obtained through both remote and manual fracture mapping. The cut slope dip direction angle (CSDD) varied between 140° and 245° at every 15° for the selected part of the open pit mine to investigate stability. The instability cumulative probabilities are calculated for cut slope dip angles between 10° and 90° at every 10°. The variability of the discontinuity orientation and shear strength is incorporated in the probabilistic block theory analysis. Discontinuity orientation is treated as a bivariate random variable including the correlation that exists between the dip angle and dip direction.

The deterministic analysis provided the following results: (a) the MSSA range between 62° and 74° for DRC rocks, and between 56° and 88° for DP rocks for the CSDD values in the range 140-245°; (b) when the CSDD is between 185° and 200°, the MSSA reached the minimum value of 62° for DRC rocks; when the CSDD is 230°, the MSSA reached the minimum value of 56°for DP rocks; (c) hence, 185°-200° and 230° seem to provide the worst CSDD for possible instability of slopes in the DRC formation and DP formation, respectively; (d) within the CSDD range of 140° to 245° the slope seem to be stable for both DRC and DP formations for cut slope dip angles less than 56°.

Results of deterministic and probabilistic block theory analyses show very good agreement on the failure modes and the worst and best case CSDD values for both DRC and DP rocks. For DRC rocks, for each CSDD angle, the MSSA obtained through the deterministic analysis was found to be about 12° to 24° higher than the MSSA obtained under the probabilistic analysis corresponding to zero instability cumulative probability. For DP rocks, for each CSDD angle, the MSSA obtained through the deterministic analysis was found to be about 10° to 28° higher than the MSSA obtained under the probabilistic analysis corresponding to zero instability cumulative probability. These differences resulted from the variability of the discontinuity orientations. The results confirmed that the design value selected for MSSA for a particular region in the open pit mine based on the deterministic block theory analysis can be on the unsafe side. In summary, the results showed clearly the superiority of probabilistic block theory analysis over the deterministic block theory analysis in obtaining additional important information with respect to design of rock slopes.

ARMA 15-0839

Evolution of ground support practices applied to low quality, squeezing rock at depth

John Henning[1]

[1] *Goldcorp*

ABSTRACT: Low quality rock is encountered in many manifestations in underground hard rock mines, ranging from weak and poorly consolidated rock to highly altered or foliated rock. Lateral mine developments driven in low quality rock pose on-going challenges to a mine operator, as ground stability issues, such as caving of under-supported ground, drift closure due to surface deformation or buckling processes, and degradation of exposed rock surfaces are a persistent concern. For many operators, ground support design is an iterative process, as support practices are refined with time. This paper presents a case example of a rationale used to develop a support strategy for

an isolated drift within squeezing Talc-Schist rock at depth. Surface and in-situ instrumentation, numerical modelling simulation, and field trials of a variety of support systems were used to assess conditions and to establish a path forward for long term stability.

Technical Session 25 – California West
Hydraulic Fracture Novel Technologies & Monitoring
Tuesday, June 30, 2015, 02:00 pm - 03:30 pm
Chairs: Neal Nagel & Fatemeh Rassouli

ARMA 15-0514

On The Importance and Impact of Key Geomechanical Parameters in Unconventional Plays

Neal Nagel[1], Marisela Sanchez-Nagel[1]
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Numerous definitions of what makes Unconventional Plays 'unconventional' have been put forth from the reliance on horizontal wells and hydraulic fracturing technology to the often ultra-low permeability (as low as single-digit nano-darcy) of the matrix. However, an important key to Unconventionals is the geomechanics of hydraulic fracturing in reservoir formation with natural fractures and/or weakness planes (e.g., bedding planes). In this paper, the authors review the importance and impact of critical geomechanical parameters based upon both numerical simulations and field data.

While commercial hydraulic fracturing has been conducted for more than 65 years, HF design has been based upon the assumption that equal half-length, bi-planar fractures will development and the dominant control on fracture length is fracture height growth, which itself is dominantly controlled by the vertical profile of the minimum in-situ principal stress, Shmin. However, when hydraulic fractures interact with natural fractures and weakness planes, the interactions are controlled by much more than the vertical profile of Shmin.

The authors, and others, have shown that the interaction between a propagating hydraulic fracture and natural fractures and weakness planes is affected by: 1) all three principal stress magnitudes; 2) the anisotropy in the stress magnitudes; 3) the orientation of the stress field; 4) in-situ pressure (e.g., pressure within the natural fractures and weakness planes); 5) natural fracture and weakness plane density and connectivity; 6) natural fracture and weakness plane orientation relative to the stress field; 7) natural fracture and weakness plane mechanical properties (elastic properties such as stiffness as well as strength properties such as cohesion and friction coefficient); 8) natural fracture and weakness plane initial aperture; and 9) operational parameters during the hydraulic fracture stimulation (e.g., rate, volume, and viscosity).

In the paper, we review the impact of each of these parameters in detail and provide quantitative examples of their individual impact. From these, we rank their importance as well as provide recommendations for data acquisition to obtain these important parameters.

The results of paper serve as an important guideline for the evaluation of critical geomechanics parameters in the design and interpretation (particularly from microseismic data) of hydraulic fracturing operations in Unconventional Plays when natural fractures and weakness plays are present.

ARMA 15-0806

Discrete Element Modelling of Microseismic Energy Associated with Hydraulic Fracturing in Natural Fractures Reservoirs

Michael Fry[1], Hemali Patel[1], Ivan Gil[1], Jim Hazzard[2], Branko Damjanac[2]
[1]BP, [2]Itasca Consulting Group, Inc.

The contribution of natural fractures to well performance in hydraulically fractured horizontal wells in shale reservoirs is not fully understood. To better understand the influence of natural fractures on well performance, numerical modelling simulations are performed. For this particular case study, a discrete element modelling software is used to simulate the hydraulic fracturing process in shale.

Two cases are analysed, one with the presence of natural fractures and the other without natural fractures. For the first case, the modelling results shows that critical stressed natural fractures have shear failure caused by the injected water from the hydraulic fracturing process, as well as tensile failures on the extreme limits of natural fracture planes. For the case without natural fractures, there are only tensile failures associated with the hydraulic fracturing process. The microseismic energy of these shear and tensile failures events are simulated by the modelling software and recorded as a function of time or amount of fluid injected. Analysing the results from both cases, there is significant difference in the number and magnitude of microseismic events. A variation in the coefficient b of the Gutenber-Richter's empirical formula for the magnitude-frequency relationship is observed with and without the presence of natural fractures. Similar variations in b value measurements are measured using downhole microseismic measurements from hydraulic fracturing in horizontal well operations in the Eagle Ford shale. For the downhole microseismic magnitude-frequency relationships, it is recommended to use the coefficient b of the Gutenber-Richter's empirical formula to indicate the presence or the lack of natural fractures in shale reservoirs.

ARMA 15-0408

Fracture Dimension Investigation of Laboratory Hydraulic Fracture Interaction with Natural Discontinuity using Acoustic Emission

Jesse Hampton[1,2], Luis Matzar[1], Dandan Hu[1], Marte Gutierrez[2]
[1]Halliburton, [2]Colorado School of Mines

Hydraulic fracturing (HF) is performed in unconventional oil and gas as well as enhanced geothermal systems (EGS) reservoirs to enhance formation permeability and create a conductive pathway for fluid flow to one or multiple wellbores. Typically, energy production requires the existence of a densely naturally fractured medium or a complex hydraulic fracture network or both. When targeting a naturally fractured reservoir, HF is meant to provide a connection between these natural fractures to generate very large regions of hydraulically connected rock for production. Although hydraulic fracturing is performed often in naturally faulted or fractured media, the geometry and effectiveness of the HF crossing natural discontinuities is not well understood. To study HF interactions with discontinuities, laboratory HF tests were performed which contained an idealized case of one large angled discontinuity, or natural fracture (NF). Two-block sample sizes of $15 \times 15 \times 25$ cm^3 were subjected to true triaxial confinement prior to wellbore placement and completion. Acoustic emissions (AE) were monitored through the fracture initiation, propagation and HF-NF interaction process. In depth post-test analysis was performed on AE microcrack data in order to characterize the hydraulic fracture as well as determine effectiveness of the HF crossing the discontinuity. Individual microcrack mode of failure was determined as well as relative volumetric deformation using moment tension inversion techniques. Comparisons were made between source mechanism information of microcracks on both sides of the NF in order to determine if changes in failure characteristics occurred. Post-test visualization of the hydraulic fractures at the surface as well as with CT-imaging provided an image of severe fracture dimension reduction, especially fracture width, crossing the NF. AE characterization was compared with visual inspections to determine if AE source parameters correlated with observed post-fracture imaging data. Implications of drastic HF width reductions crossing NF include under-predictions of stimulated reservoir volume from field scale AE data, as well as reduced production.

KEY WORDS: Hydraulic Fracturing (HF), Natural Fracture (NF), Acoustic Emission (AE), Moment Tensor Analysis, Granite, Laboratory

ARMA 15-0141

Development of a test setup capable of producing hydraulic fracturing in the laboratory with image and acoustic emission monitoring

Bruno Gonçalves da Silva[1], Bing Li[1], Zabihallah Moradian[1], John Germaine[1], Herbert Einstein[1]
[1]*Massachusetts Institute of Technology*

Hydrocarbon extraction is relying progressively more on hydraulic fracturing stimulation of shale reservoirs in order to enhance their permeability, and consequently, their productivity. Enhanced Geothermal Systems (EGS) also rely on hydraulic fracturing to create fractures in the hot rock through which water is circulated in order to subsequently recover its heat at the surface.
While hydraulic fracturing has been extensively used in field applications, the fracturing processes involved in this method are still not well understood. Since data obtained from field hydraulic stimulations may be very difficult to interpret, laboratory testing may play a major role in understanding the way fractures initiate, propagate and interact when hydraulically stimulated.
This paper describes a test setup developed at MIT, which allows one to apply hydraulic pressure to flaws, or existing fractures, leading to the initiation and propagation of fractures. The test setup consists of (1) an enclosure designed and built at MIT in which water pressures up to 10 MPa can be generated, (2) a high speed camera that captures the last seconds of a test at 14,000 frames per second, (3) a high resolution camera that captures frames every 2 to 5 seconds throughout a test, and (4) an acoustic emission system that monitors the micro-seismic activity throughout the test.
The test setup has been successfully used in several tests in granite. An example of the type of results obtained in a test is shown.

ARMA 15-0612

Development of Experimental Apparatus for Real-time Observation of Hydraulic Fracture in Unconsolidated Sands by X-ray CT method

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Oil and gas in unconsolidated sands have become the targets of development, and hydraulic fracturing has been applied to enhance the production. The unconsolidated sands have properties of rather higher permeability and fairly weaker bond between particles compared with hard rocks. For those reasons, fracturing behavior in unconsolidated sands is not suitably represented by existing models for brittle, linear-elastic rocks. In order to clarify the characteristics of hydraulic fracture in unconsolidated sands, we have been developing laboratory experimental apparatus which allows us to observe in real-time the hydraulic fracture behavior by the X-ray CT method. A specimen should have a size to be sufficiently large for the fracture growth, i.e. more than few hundreds mm, and the inside of such a large specimen should be visualized within a time interval to be sufficiently short compared with a time period of few hundreds seconds required for fracture initiation and growth. The specimen should be subjected to tri-axial compression for simulating subsurface conditions. Considering those requirements, we prepared several types of experimental apparatus and finally succeeded to develop an apparatus to realize the real-time observation. The apparatus allows us to obtain within a few seconds a CT image of a longitudinal slice of the fracture in the growing direction. The results shows peculiar characteristics of the hydraulic fracture in unconsolidated sands. For an example, the fracturing fluid can reach the fracture tip and invade further into the rock matrix, as shown in Fig. 1, and therefore a non-wetted zone is not developed at the fracture tip in contrast to the case of hard rocks. Such fluid invasion should play an important role in the mechanism of fracture formation in unconsolidated sands.

Keywords: Hydraulic fracturing, Soft rock, Unconsolidated sands, Laboratory experiment, X-ray CT method, Visualization

ARMA 15-0318

Pickling the Gas Shale in Water or Water Vapor

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We have been conducting shale research for more than four decades in Oilfield as well as Coal mines. Since late 1960s, our work has dealt with troublesome shale as a source of well bore instability or coal mine roof falls near ventilation shafts. We quickly found that the shale issues must be addressed by simultaneously taking into account the combined chemical, physical, and mechanical properties of the shale. To accomplish this, we introduced the thermodynamic properties of the shale based on its specific percentage of clay content. This technique, along with sound and practical petroleum engineering practices, guided us to successfully design the mud systems, tailored for drilling long sections of troublesome shale, and resolve the issues of well bore instability, ultra fine contamination of drilling fluid, lost circulation, and slow drilling. In addition to considering shale as a source of *hazard*, since mid 1970s, we have been involved with research that considers shale gas/liquid as a viable economic *resource* and how to best extract these natural energy resources from a shale that could be categorized as “troublesome shale.”

Regarding the recovery of the natural energy resources, in this work we share our recent results and conclusions about the following questions and their significance to both Petroleum Gas/liquid Production and Roof Control in Coal Mining:

1. At what specific sites is the gas stored within the shale mass? 2. For how long, at a minimum, should we shut-in the well after hydraulic fracturing for optimal gas production results? 3. How do the micro-fracture networks in shale grow? 4. What kind of fracture develops in these networks? 5. At what specific sites do these micro-fracture networks initiate? 6. Why these micro-fractures do not develop in some samples that have almost the same type and concentration of clay minerals? 7. How many types of gas flow behavior can we expect from a “pickled” gas shale? 8. Is the gas flow from the “pickled” gas shale cyclic within a short time or steady over a long period? 9. Could there be any relationship between the activated sites of shale where the “free gas,” exists and the localized “pore pressure” in the “pickled” shale mass? 10. Is there a relationship between the appearance of a fault and and the "free gas" within the same shale sample? 11. Is the fault appearing in the “pickled” shale sample strictly a normal fault? 12. Is there any water in the gas shale that seemingly appears dry?

Technical Session 26 – California East Coupled Process Modeling

Tuesday, June 30, 2015, 02:00 pm - 03:30 pm

Chairs: Jonny Rutqvist & Laura Blanco Martin

ARMA 15-0425

Coupled Euler-Lagrange Simulation of the Response of a Tunnel in Jointed Rock to Explosive Loading

David Steedman[1]

[1] *Los Alamos National Laboratory*

The US Department of Defense, under the auspices of the Defense Threat Reduction Agency (DTRA), has for decades been studying the response of tunnels to explosive loading. Efforts have included experiments ranging from laboratory-scale through full-scale field tests with instrumented response. These tests are intended to provide benchmarks for analytical approaches to predict vulnerability of actual structures to possible loading scenarios.

Small-scale experiments have included MIGHTY NORTH and JOLT. MIGHTY NORTH included limestone bars stacked around an aluminum-lined “tunnel” and included a cylindrical explosive charge to load the tunnel in plane strain to test early 2-D computer codes. Successful modeling of this event using the Abaqus finite element code validated our approach.

Subsequently, the JOLT (Jointed Limestone Test) experiments were accomplished to allow validation of more recent 3-D computing capabilities. Each JOLT event consisted of 64 layers of ½-inch cubes of limestone stacked imbricate style around two scaled tunnels. Each test was loaded with a spherical Composition B explosive source. The test beds were instrumented and these data, along with test bed post-event de-construction, provided results for comparison of computer simulations to the experiments.

We used the fully coupled Euler-Lagrange capability of Abaqus to model the event. The ¼-symmetry simulation consisted of an Euler regime for the high deformation explosive source region. A Lagrange regime included 37,000 individual 64-element continuum cubes with contact. The computed results compare favorably to the test data for both the active instrumentation and the damaged test bed configuration.

We will include results from both MGHTY NORTH and JOLT in this paper. This abstract has been approved for release as LA-UR-14-28474.

ARMA 15-0123

Numerical Manifold Modeling of Coupled Hydro-Mechanical Processes in Fractured Porous Rock Masses

Mengsu Hu[1], Yuan Wang[1,2], Jonny Rutqvist[2]

[1]*College of Civil and Transportation Engineering, Hohai University,* [2]*Earth Sciences Division, Lawrence Berkeley National Laboratory*

Abstract: The key problems of coupled hydro-mechanical modeling in complex fractured rock masses are the discontinuous nature of rock fractures in both the hydraulic and mechanical fields and their couplings. In this study, we develop a new Numerical Manifold Method (NMM) model to simulate coupled hydro-mechanical (HM) processes in fractured rock, making full use of the NMM two-cover-meshing system and its capability of unified analysis of continuous and discontinuous media. We constructed the two-cover-meshing system with fixed triangles as the mathematical covers and cut mathematical covers into physical covers by boundaries for defining the integral domain. In our model, we regarded fractures as a special medium with different material properties from that of the rock matrix and thereby could discretize the fractures and rock matrix with a uniform mathematical grid. In such a system, we could consider fractures by the following two approaches: (1) fractures and surrounding rock are discretized in separate elements and the interactions between fractures and rock matrix is imposed through penalty for mechanic analysis and Lagrange multiplier for hydraulic analysis; (2) fractures and rock matrix share the same elements in which the discontinuities associated with fractures are represented by jump functions in both mechanic and hydraulic fields. We used an energy-work model to construct the total potential energy considering all work related to mechanics and water flow and derived the equilibrium equations by minimizing the total potential energy, providing a form consistent with that derived from the conventional Galerkin`s method based on Biot's equations. As a result, couplings are considered by the displacements and the hydraulic heads being solved synchronously (direct coupling) and by changing the fracture permeability and fracture stiffness as functions of stress (indirect coupling) implicitly in each time step. We first used a consolidation example to examine the validity of the model for direct pore-volume coupling. We then applied the two fracture approaches for modeling an example involving water injection into a single fracture and compared the results with existing FEM results. Finally, we applied the two approaches to a rock mass containing several sets of fractures and changed the fracture dimensions. We proved that the first approach is effective for dominant fractures with large aperture or width (such as faults or major filled fractures) and the latter is efficient when fractures are thin and dense with intersections. This NMM model will be extended to analysis of large-scale hydraulic fracturing and fracture network stimulations to be applied in energy production.

Keywords: Numerical Manifold Method, fractured rock, hydro-mechanical direct coupling, indirect coupling, Lagrange Multiplier, jump function

ARMA 15-0587

Coupled Modeling of the Strength Development and Distribution within Cemented Paste Backfill Structure

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Cemented paste backfill (CPB) receives great interest as one of the most commonly used ways in mine backfilling around the world. The usage of CPB greatly contributes to the disposal of mining tailings waste from the surface, increasing working place stability and having the ability to extract more minerals safely. Although CPB has been successfully implemented and extensively used in underground mining operations worldwide, it remains a relatively new technology. The industry is still on a learning curve with respect to the behavior, performance properties and optimal design of CPB structures.

Once placed in the underground mine excavations (stopes), CPBs have to satisfy certain mechanical resistance requirements to ensure a safe underground working environment for all mining personnel. Moreover, mine backfill failures have considerable financial ramifications and can result in fatalities or injuries. One of the key parameters for assessment of the mechanical resistance of CPB structure and often used in the practice is its strength; namely, unconfined compressive strength (UCS). Knowing the time at which the CPB reaches its reasonable strength is very important for reducing the mining cycle and ensuring the safety of mine workers.

In this paper, a numerical model is developed (and implemented into FLAC software) for predicting the UCS development and distribution of undrained hydrating CPB structure, taking into account the coupled effects of temperature (thermal factor) and binder hydration (chemical factors). Data from field and laboratory studies are employed to validate the developed model. The validation results show a good consistency between the predicted and the field and laboratory results. The developed tool is then used to simulate the strength development within CPB structures in several practical cases. The developed tool can contribute to more cost-effective and safer design of CPB structures.

ARMA 15-0680

Thermal-Hydrological-Mechanical Modelling of Shear Stimulation at Newberry Volcano, Oregon

Torquil Smith[1], Eric Sonnenthal[1], Trenton Cladouhos[2]
[1]Lawrence Berkeley National Lab, [2]AltaRock Energy, Inc.

Fluid injection at the Newberry Volcano Enhanced Geothermal Demonstration site, was aimed at enhancing permeability through shear stimulation of the existing fracture network. A 3-D Thermal-Hydrological-Mechanical (THM) model was developed for simulation using TOUGHREACT-ROCMECH (Kim et al. 2012) using initial thermal and hydrological properties developed through calibration to prior injection tests (Sonnenthal et al., 2012; Rinaldi et al., 2013). We coupled the TH model to mechanical stress, strain and shearing, to evaluate injectivity increases observed during the 2014 hydrological stimulation. We use Mohr-Coulomb (MC) criteria for shear relief of effective stresses, and allow for simultaneous shearing on one, two or three planes. Initial regional stresses, based on Cladouhos et al. (2012), have the minimum stress approximately oriented N-S. Simulations consider changes in total stress and in effective stresses owing to pressure and temperature changes during fluid injection. We assume a cubic law for permeability changes due to fracture dilation upon shearing.

Because the fracture mechanical and hydrological properties are not well known, sensitivity studies were performed to determine a set of properties that could capture increased flow rates observed during the 2014 stimulation. Initial bulk porosities and permeabilities in the reservoir unit were estimated to be 0.03, 5e-18 m^2 in the E-W direction, and 1e-17 m^2 in the N-S and vertical orientations, respectively, with about an order of magnitude higher permeabilities in known fracture zones. Properties varied were the fracture dilation angle, the cohesion, and the initial fractions of fracture porosity and permeability. The best set of properties assumed that initially 0.1% of the bulk porosity was due to connected fractures, the rock had 2 MPa cohesion before fracturing or fracture re-activation, and that shearing fractures have a 2 degree dilation angle. Negligible cohesion resulted in more shearing at the lower pressures of the earliest stages of injection and higher flow rates than were measured. Assuming an initial fracture porosity that was 3.3 % of the bulk porosity resulted in negligible shear enhancement of permeability and underestimated flow rates. A smaller dilation angle (0.6 degrees) and a lower assumed fracture porosity proportion (0.0007), resulted in an intermediate amount of shear permeability enhancement, and lower flow rates than were observed. In these simulations, the elements close to the open section of well undergo simultaneous shearing on two shear surfaces, keeping two principal stresses equal, as the difference between them and the third principal stress is lessened through shearing. This study illustrates the benefits of using coupled THM models that include simultaneous shearing on multiple surfaces, and considering permeability changes as function of shear displacement.

ARMA 15-0809

Near Field Phenomenology for the Source Physics Experiments

David Steedman[1], Christopher Bradley[1]
[1]*Los Alamos National Laboratory*

The Source Physics Experiments (SPE) is a series of various size Sensitized Heavy ANFO (SHANFO) explosive sources detonated in a borehole in jointed granite. The cylinder-shaped shots are grouted in the borehole to couple the energy to the rock. A number of free-field and surface accelerometers are in place to monitor the ground shock.
We demonstrate a hydrodynamic numerical simulation with a detailed site model that mimics the near-field velocity environment. This includes modeling the cylindrical explosive, the grout-filled borehole, and explicit modeling of the site joint sets. This approach is accommodated through use of the Abaqus Coupled Euler-Lagrange (CEL) code which allows simultaneous solving of an Eulerian domain to model the high-deformation source region with a Lagrangian domain that includes the complex geology with full contact. Various simulations and comparisons to data provide insight into the possible source of theoretically unexpected shear phenomena.
The effect of joints on radial shock propagation is demonstrated by comparing results from both 1-D and 3-D simulations to recorded data. Both simulations apply the same laboratory-determined characteristics of intact core response. But the 3-D approach also includes a realistic model of the borehole emplacement geometry, including stemming materials, as well as explicit rock joints based on borehole logging. Inclusion of joints has the effect of delaying the arrival, reducing the amplitude and broadening the pulse for the radial response.
The joint response model, also developed from laboratory data, provides insights on a possible response mechanism for introducing shear content. Ground shock from a SPE-like source should contain very little transverse component. However, these data (*e.g.*, Figure 2) display unexpected character. Immediately following shock arrival the transverse component is quiescent as expected from theory. However, concurrent with the radial peak a sudden change in amplitude occurs in the transverse component. We match this effect by including “elastic slip” in addition to the standard Coulomb friction law for joint tangential response. The resulting computed waveform, included in mimics the data. We hypothesize that the passing compressive wave limits joint tangential movement. When the shock front unloads (*i.e.*, just after radial peak velocity) a sudden release of the joint allows for greater motion. This likely leads to the shear response that far field seismic stations sense.
This abstract has approved for public release under LA-UR-14-28791.

ARMA 15-0038

Mixed Finite Element Method applied to Non–Euclidean Model of Inelastic Deformations

Egor Vtorushin[1], Vitaly Dorovsky[1], Evgeny Romensky[1]
[1]*Baker Hughes*

Rock behaviour frequently does not fit the classical theory of continuum mechanics because of rock aggregated granular structure. Particularly, rock fracturing may be accompanied by zonal disintegration formation.

The key to building the non-classic model of rock fracturing is the granulated structure. Deformations of solid bodies with microscopic flaws can be described within the scope of non-Euclidean geometry, and non-trivial deformation incompatibility can be referred to as a fracture parameter.

The new continuum model presented in this paper enables the prediction of the zones initializing and developing as a periodic structure. The non–Euclidean description of phenomenon initiates an appearance of two new material constants that by analogy with classic model called 'inelastic' moduli. The coupled model must comprise the fourth–order parabolic equation on disintegration thermodynamic parameter be solved with the classical hyperbolic system of equations for the dynamics of continuous media.

This paper presents the semi-discrete mixed weak formulation of the coupled problem. Based on this formulation and the theta method for time discretization, the following numerical algorithm was built: explicit scheme for the elasto-dynamic variables evaluation and implicit scheme for diffusion of the disintegration parameter. For spatial approximations, the mixed-finite element method is applied.

The 2D model of formation of disintegration zone in a strip under axial compression was solved numerically. The zone magnitude and site that can be described by the term 'disintegration scale' are determined by values of the 'inelastic' moduli.

Therefore, the numerical model is established on the new non-Euclidean continuum model is capable of predicting formation of a disintegration field periodic structure. The second important result is that spatial direction of the disintegration parameter propagation is established as shown on the figure below. The new continuum model and its numerical implementation support a range of fracture mechanics of rock problems such as rock cutting.

Keywords: Mixed finite elements, in-elasticity, zonal disintegration phenomenon, non-Euclidean continuum model, coupled models, rock heterogeneity and scaling.

Technical Session 27 – Elizabethan AB
Geophysical Properties of Rocks

Tuesday, June 30, 2015, 02:00 pm - 03:30 pm

Chairs: Seiji Nakagawa & Brian Bonner

ARMA 15-0245

Monitoring of Mechanically-Induced Damage in Rock using Transmission and Reflection Elastic Waves

Anahita Modiriasari[1], Antonio Bobet[1], Laura J. Pyrak-Nolte[1]
[1]*Purdue University*

Crack initiation, propagation, and coalescence from pre-cracked rock specimens were detected in an experimental study by monitoring seismic wave transmission and reflection through rock. The experiments were conducted on prismatic Indiana Limestone specimens with two parallel pre-existing cracks (flaws). The specimens were 203.2 mm high, 101.6 mm wide, and 38.1 mm thick. The two flaws were made using a water jet. The length of the flaws was 25.4 mm and the depth of the flaws penetrated the entire thickness of the specimen. The specimens were subjected to uniaxial compression loading to induce crack initiation, propagation and coalescence. Digital image correlation was used to observe the cracking process around the tips of the flaws by observing the surface displacements. In the experiments, three different types of cracks were distinguished based on their geometry and propagation mechanism: tensile cracks, coplanar shear, and oblique shear cracks. The main purpose of this study was to characterize the cracks originating from the flaw tips by ultrasonic wave imaging. For this purpose, compressional and shear wave pulses were transmitted and reflected continuously through the specimen while the uniaxial compression load increased. Compressional (P) and shear (S) wave transducers were embedded into steel platens placed on each side of the specimen and supported by springs. The normalized amplitude of the transmitted waves (for shear waves with horizontal polarization) was observed to decrease with increasing uniaxial compression load. This reduction in amplitude, however, intensified prior to tensile crack initiation. In addition, a further drop in amplitude was observed close to coalescence stress. These changes in amplitude occurred at least 1.3 MPa before the detection of tensile cracks by DIC imaging. In addition, the normalized amplitude of reflected signals (from the flaw tips) increased significantly before tensile and shear crack initiation. A change in slope of the transmitted waves occurred prior to detection with DIC. The experiments indicate that changes in transmitted and reflected seismic waves serve as a promising method to detect crack initiation inside rock, as well as to determine the location of new cracks.

ARMA 15-0651

Extremely slow, dispersive seismic wave propagation within a fluid-filled fracture and their electrokinetic effects

Seiji Nakagawa[1], Steven Pride[1], Valeri Korneev[1]
[1]Lawrence Berkeley National Laboratory

Open and partially open fractures can trap and guide seismic (pressure) waves within the fluid contained in their aperture. Similarly to the Biot's slow compressional waves in fluid-filled porous media, these waves—called Krauklis Waves—are highly dispersive (the velocity depends on the frequency) and strongly dissipative, and their propagation velocity can be far below the acoustic velocity of the fluid at low frequencies (tens of a few hundred m/s for a few hertz up to kilohertz). For highly permeable fractures, however, the fluid-guided waves can propagate for a substantial distance away from the source, which may allow us to use this type of waves for subsurface fracture detection and characterization. Also, for a fracture filled with permeable gouge (such as silica sand) saturated with water, an electrical field can be produced by the wave-induced fluid motion. Under ideal conditions, the produced electrical signature may be detected away from the fractures. This paper presents theoretical predictions and laboratory experiments on the guided wave's behavior and on the wave-induced electrokinetic effect for an open, partially open (with finite mechanical fracture compliance), and proppant-filled fractures. The laboratory experiments were conducted using an analogue fracture consisting of a pair of slender glass plates with a water and proppant-filled gap between them. Propagation of pressure waves along the plates was measured along an array of measurement points (holes drilled in the glass plate) using a pressure transducer. Simultaneously, at the same locations, the electrical potential changes induced by the passing waves were measured and correlated to the pressure amplitude and the electrolyte concentration of the water.

ARMA 15-0554

Numerical investigation of the relationship between fracture shear compliance and conductivity anisotropy

Joseph Morris[1,2]
[1]Lawrence Livermore National Laboratory, [2]Schlumberger

Measurement of the shear to normal compliance ratio is one of the few remote sensing techniques available for estimating the in situ properties of fractures. We present an accurate yet efficient method for predicting the normal and shear compliance of fractures using an asperity-based approach. The resultant capabilities provide an efficient, versatile tool for predicting the normal and

shear compliance of fractures with arbitrary roughness under a given level of closure stress. We apply the method to the prediction of evolving shear compliance under closure stress. We also calculate the corresponding anisotropic conductivity of the deformed fractures and find that the direction of highest shear compliance correlates well with the direction of highest fracture conductivity. This suggests that the degree of shear compliance anisotropy may be an indicator of conductivity anisotropy in natural fractures over a range of stresses. We discuss the implications of these results for remote sensing of fractures and appropriate upscaled treatment of coupled flow and mechanics in fieldscale models.

ARMA 15-0382

Acoustic Wavefront Imaging of Orthogonal Fracture Networks subjected to Bi-axial Loading

Siyi Shao[1], Laura Pyrak-Nolte[1]
[1]*Purdue University*

Carbonate reservoirs that are often contain steeply dipping fractures and horizontally oriented stylolites that lead to the formation of orthogonal fracture networks. Interpretation of elastic waves propagated through orthogonal fracture networks is complicated because of the potential existence of guided modes along and between fractures, multiple internal reflections, as well as scattering from fracture intersections. The existence of some or all of these potentially overlapping modes depends on the local stress field that can preferentially close or open either one or both sets of fractures. For this study, an acoustic wavefront imaging system was used to examine the effect of bi-axially loading conditions on elastic wave propagation in isotropic media with synthetic orthogonal fractures.

Two cubic aluminum samples (~100 mm on edge) were used that each contained two orthogonal fracture sets. The horizontal and vertical fracture spacings for these two samples were 20 mm and 10 mm, respectively (Figure 1). Two computer-controlled load frames were used to apply external normal and horizontal stresses, ranging from 0 to 12 MPa, to the samples to change the specific stiffnesses of the fractures. During an experiment, a sample was submerged under water, while two spherically-focused water-coupled transducers (central frequency 1 MHz) were used as a fixed-source and a translating receiver. Each sample was scanned over a 60 mm×60 mm 2D region in 1 mm increments to map out the arriving compressional wavefront as a function of time (i.e., 100 microsecond window for 3600 signals were recorded).

When both the vertical and horizontal stresses were low (<0.2 MPa), the elastic waves were trapped in the central prismatic wave guides (Figure 1a), because the fracture stiffness was sufficiently low to prevent significant transmission across the fractures. As the vertical stress was increased (> 6 MPa), the fracture stiffness of the horizontal fractures increased which resulted in an increase in transmission across the horizontal fractures. The wavefront for this condition was confined by the low stiffness of the vertical fractures and also exhibited phase contrast between neighboring blocks (Figure 1b). When both the vertical and horizontal stresses were larger than 6 MP, for the 20 mm spacing sample, the fracture intersections produced an additional delay resulting in a wavefront geometry that appears rotated 45 degrees to the fracture planes (dashed lines in Figure 1c). For the 10 mm spacing sample, the wavefront is asymmetric and indicates that the specific stiffnesses among different fractures was not the same because of non-uniform loading.

These experiments demonstrate that the presence of orthogonal fracture sets can exhibit a range of behavior (rectangular wave guide, parallel plate wave guide) depending on the local stress conditions, and also demonstrate the importance of understanding the effect of fracture intersections on propagating waves. Interpreting elastic waves from orthogonal fracture sets requires knowledge of the local tectonic stress distribution.

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Number (DE-FG02-09ER16022) and by the Geo-mathematical Imaging Group at Purdue University.

ARMA 15-0433

New high-speed friction experiment capability for study of friction

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Recent experimental investigations of friction in rock and gouge using high-speed rotary shear apparatus demonstrate pronounced reduction in the apparent coefficient of friction at seismic slip rates greater than 0.1 m/s, which likely reflects lubrication by generation of ultrafine particles, thermal-chemical processes, and dynamic fluid pressurization within thin slip zones. Results of high-speed friction tests (rotary, triaxial stick-slip, and impact shear plate) indicate the critical slip distance for weakening depends on normal stress, slip velocity, and slip acceleration (J.C. Chang, et al., *Science*, 338, 2012). Limitations of current testing devices inhibit our ability to investigate coseismic friction weakening at all conditions of earthquake rupture (specifically slip velocity, normal stress, fluid states, ambient temperature) and develop relations for scaling (spatial and temporal) laboratory results to natural earthquake faulting. Accordingly, we are developing a testing machine specifically designed to achieve novel high speed and high acceleration load-paths for investigating friction.
This paper presents a new high-speed apparatus for double-direct and triaxial shear testing of friction at both quasi-static (1 μm/s - 0.01 m/s) and high-speed (0.02 - 2 m/s) conditions. The loading system achieves high acceleration rates (up to ~ 500 ms^{-2}) to achieve velocity steps from quasi-static to constant high speed rates with up to 4 cm high-speed displacement. This capability is intermediate between current rotary shear, triaxial stick-slip, and shear-plate impact experiments in terms of acceleration, normal stress, and slip magnitude (Figure 1). The apparatus will be equipped with a pressure vessel to allow testing at high normal stresses, pore pressures and elevated temperatures representative of moderate size earthquake conditions.
The high-speed loading system consists of coupled pneumatic and hydraulic-damping cylinders with load capability of 1.5 MN. Feedback control is not feasible at high accelerations because the rise time is too small; hence, a complete understanding of the effects of different passive control variables on the response of the system, and of the interaction between the loading system and test sample, is necessary. Dynamic analysis of sample-apparatus interaction during high-speed loading is performed to determine appropriate control-variable settings and attain the target acceleration and velocity load path. The desired velocity-step testing can be achieved by the apparatus for a range of expected sample strengths and friction behaviors. The model analysis of the high-speed loading system is validated and calibrated for the apparatus by conducting tests with and without samples of rock. We will present the model analysis, model validation, and experimental results. Initial experiments are aimed at determining how the critical slip distance for high-speed friction weakening depends on slip rate, acceleration, and normal stress.

ARMA 15-0546

Application of Refraction Microtremor (ReMi) for predicting changes in rock characterization in an underground mine.

Chase Barnard[1], Rajagopala Kallu[1], Satish Pullammanappallil[2], Travis West[2]
[1]University of Nevada, Reno, [2]Optim SDS

A study was conducted to determine the applicability of Refraction Microtremor (ReMi) in order to predict changes in geologic structure in an underground mine. ReMi involves acquiring noise data along a linear array of geophones. Data is processed to obtain shear-wave velocities underneath the array. The data for our study was collected at Turquoise Ridge Joint Venture, and was analyzed using the SeisOpt® ReMi™ (© Optim, 2014). The data was collected using horizontal geophones, placed into the ribs of the drift in a horizontal plane, rather than the industry standard placement of

vertical geophones into the ground in a vertical plane. Data was thus collected to ensure Rayleigh waves were being recorded and the integrity of the method is preserved. In order to determine whether the changes seen actually exist, shear wave velocities were measured in location of known geologic changes. In addition to changes in geologic structure, the shear wave velocities were compared with the Rock Mass Rating (RMR) of several locations. These values were used to compare with previously published values on RMR and shear wave velocity correlations. Based on the data collected, a determination was made as to whether ReMi can be effectively used to determine changes in geologic structure in an underground mine, as well as, whether any correlation lies between shear wave velocity and RMR. In addition, ReMi was used as a tool to determine the extent of unraveling of ground behind shotcrete support. This was used to determine the extent of rehab required in areas of known unraveling and to help distinguish locations where unraveling may not be visible, but is still taking place.

Technical Session 28 – Elizabethan CD
Deep Mine Rock Mechanics

Tuesday, June 30, 2015, 02:00 pm - 03:30 pm

Chairs: Hamid Maleki & Ted Klemetti

ARMA 15-0553

Borehole Breakout Analysis to Determine the In-Situ Stress State in Hard Rock

Gabe Walton[1], Kathy Kalenchuk[1], Colin Hume[1], Mark Diederichs[2]
[1]Mine Design Engineering Inc., [2]Queen's University

The engineering design of excavations at depth can be strongly influenced by assumptions of the magnitude and orientation of in-situ principal stresses. Assumed stress states can have significant implications to the feasibility of mining projects, as stope design, strategic sequencing and permanent infrastructure siting are major controls on development costs and production rates and henceforth life of mine economics. Three-dimensional numerical models are commonly utilized to simulate the changes in the stress state induced by mining activities. The far field, pre-mining stress state is commonly a major assumption controlling modelling behaviour. This is typically a global assumption to the entire mining area of interest, when in fact the actual magnitude and orientation of the regional stress tensor will vary based on localized geological controls such as lithology and structural domains. This paper provides a discussion on how to minimize uncertainty in pre-mining stress state assumptions by utilizing analytical and numerical methods to back-calculate far field stresses from observations of borehole breakout. A case history is presented examining breakout observed in acoustic televiewer data in a deep shaft pilot hole. The orientation and magnitude of the in-situ stress field varies with depth as the borehole transects different lithological units and structural features. Analytical methods and two-dimensional models focus on how the geometry of breakout features provides valuable information to approximate the in-situ stress state.

ARMA 15-0296

Dynamic tensile failure of rocks subjected to simulated In situ stresses around underground openings

Kaiwen Xia[1], Bangbiao Wu[1], Rong Chen[2]
[1]University of Toronto, [2]National University of Defense Technology

Tensile failure of rocks is the main problem in underground rock engineering projects, in which rocks are subjected to dynamic disturbances while under high In situ stresses. For example, in deep mine, the bending of the roof and the buckling of the pillar would induce static tensile stress state. When disturbed by dynamic loads from blasting, seismicity or rockbursts, the structures would be vulnerable to tensile failure. From microscopic perspective, pores and microcracks in rock materials are potential sources of tensile failure because of stress concentration. Even though the far-field load is compressive, the local stresses around these inhomogeneities may be tensile. Dynamic disturbance would promote the generation, propagation and nucleation of defects, and lead to the tensile failure of the rock materials.

In deep mining activities, blasting induced compressive stress wave would be reflected as tensile wave at a free surface around the openings, which would facilitate the tensile failure of the deep rock since it is much weaker in tension than in compression. It is thus critical to understand the dynamic tensile failure of rocks subjected to static tension for deep rock engineering applications. A modified split Hopkinson pressure bar (SHPB) system is adopted to load Brazillian disc (BD) samples statically, and then exert dynamic load to the sample through stress wave generated by impact. The pulse shaper technique is used to generate a slowly rising stress wave and thus to facilitate the stress equilibrium of samples during each test. Five groups of Laurentian granite (with tensile strength of 12.8 MPa) BD samples under the pre-tension stress of 0 MPa, 2 MPa, 4 MPa, 8 MPa, and 10 MPa are tested under different loading rates.

The result shows that the dynamic tensile strength of the rock decreases with the increase of pre-tension stress, which is easy to understand because pre-tension stress weakens the rock sample. It is also observed that under the same pre-tension stress, the dynamic tensile strength increases with the loading rate, revealing the so-called rate dependency that is common for engineering materials. Furthermore, it is found that the loading rate sensitivity of the rock increases with the increase of pre-tension stress. A qualitative explanation for this phenomenon is that more microcracks are generated and activated under higher pre-tension stress, resulting in a more viscous material. Based on the results, an empirical equation is proposed to fit the data and explain the dynamic tensile behaviour of rock under pre-tension stress. A physical model is used to simulate the dependency of the dynamic tensile strength of rock on the pre-tension stress and the loading rate, which is shown to be in good agreement with the experimental results.

ARMA 15-0776

Strength and Elastic Properties of Paste Backfill at the Lucky Friday Mine, Mullan, Idaho

Jeffrey Johnson[1], Joseph Seymour[1], Lewis Martin[1], Michael Stepan[1], Anthony Arkoosh[1], Tyler Emery[2]

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At underground mines where cemented backfill is used for ground support, backfill strength properties are an important design consideration, particularly for underhand cut-and-fill mining operations where employees work directly beneath the placed fill. This paper summarizes the results of a case study conducted in cooperation with the Hecla Mining Company to determine the strength properties of paste backfill consisting of cemented mill tailings which are hydraulically placed in narrow vein stopes in a deep underground silver mine in northern Idaho. Unconfined compression tests and direct and indirect tensile tests were conducted with core samples obtained from paste backfill slabs that were recovered from a roof fall in a backfilled area of the mine. Two types of indirect tensile tests were conducted—Brazilian tests and splitting tensile tests. In addition to standard direct tensile tests with samples equipped with glued end-platens, a shotcrete adhesion test system developed by NIOSH researchers was adapted for conducting in-situ direct tensile tests on the backfill slabs themselves. Further unconfined compression tests were conducted with strain-gauged core samples to determine the elastic properties of the paste fill material (i.e., Young's Modulus and Poisson's ratio).

Test results indicated the following average strength properties for the paste backfill samples: 601 psi (4.15 MPa) compressive strength; 70.4 psi (0.49 MPa) indirect tensile strength, and 48.5 psi (0.33 MPa) direct tensile strength. Similar results were obtained from the Brazilian and splitting tensile tests with this fine-grained material. As expected, the direct tensile test results were much lower than the average results of the indirect tensile tests. The in-situ direct tensile tests indicated an even lower boundary for tensile strength at approximately half the average result of the standard direct tensile tests. This may be an indication of in-situ weaknesses in the mass material that are not reflected in the intact core samples. The results of compression tests with strain-gauged samples of the paste

backfill indicated an average Poisson's ratio of 0.17 and an average Young's Modulus of 0.52 x 10^6 psi (3.59 GPa), 0.33 x 10^6 psi (2.28 GPa), or 0.16 x 10^6 psi (1.10 GPa) depending on the compressive stress range, 0-30%, 30-60%, or 60-90% of the ultimate compressive strength, respectively. Using a small hydraulic test machine and in-situ core samples collected from backfilled stopes with a custom-designed, post-mounted, vertical core drill, the mine staff has measured comparable results from unconfined compression tests and Brazilian tests conducted at the mine site. The overall findings of this study are significant because they provide much needed and seldom reported information regarding the tensile strength and elastic properties of paste backfill.

ARMA 15-0582

Influence of fine material and vertical loads on the flowability of caved rock

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Flow-ability is defined as the flow capability of a given granular material to flow under a given draw-bell geometry, and stress condition. Gravity flow of broken material highly influences efficiency and production rate in block/panel caving mines. Despite its importance in underground block/panel and sublevel caving methods, the flow mechanism of broken ore with persistence of fine material are not well understood especially under high stress condition. The main objective of this paper is to quantify the influence of fine material and vertical load on gravity flow of one draw-bell in block caving mine. Therefore, a scaled physical model was utilized to evaluate the flow-ability of caved rock under high vertical loads and different percentages of fine material. The material used in the experimental tests was crushed sulphide ore with a high aspect ratio to represent the geometry of caved rock. The particle size distribution was scaled (1:75) of the expected primary fragmentation curve of the underground´s Chuquicamata project. Flow-ability is characterised quantitatively in terms of the scaled number of hang ups in every 1000 tons of drawn rock. Based on experimental tests, this paper shows that particle size, which is noted as fines presence, and vertical stress have negative impact on the flow-ability of caved rock. The results of hang ups analyses reveal that high hang ups occur with the presence of fine material or with the application of vertical pressure. Moreover, the number and height of hang ups significantly increase by raising the amount of vertical load or fines presence.

ARMA 15-0144

Cavability, the Least Known Engineering Factor Influencing Mine Designs in Secondary Extraction Layouts

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Based on review of overburden collapse mechanism in both coal and evaporites, over the last three decades, the author finds empirical methods that are used for assessing cavability inadequate. These empirical methods suggested by Polish researchers are too simplistic offering limited usefulness for estimating face support loading without quantifying the caving characteristics of the main roof strata, ability to concentrate stress and release it in preferably nonviolent fashion. Direct measurements are needed but are rare with the exception of a set of measurement in a Utah mine.

Conceptual caving models envision mostly regular, uniform caving of overburden rocks with limited overhang affecting face support loading periodically but eventually resting on compacted gob and transferring the load to the floor. Great insight was gained in the 1980's as hydraulic pressure on the shield legs could routinely been monitored, promoting understanding of periodic weighting and caving of near seam strata. However the caving mechanism of the overburden rocks and its cyclic failure was not fully appreciated until direct measurements in the gob of the Utah Mine in the 1980's pointed to such a mechanism, as oppose to regular caving and load transfer defined by a cave angle of 21 degrees suggested by NIOSH.

Using direct measurements in the gob, back analyses of overburden collapse mechanism and other measurements over the last three decades, the author examines the caving mechanism for western US sedimentary rocks. The significance of joint orientation and persistence is highlighted as well as the critical role of stable designs including the use of barrier pillars strategically located to control load transfer and seismicity in room-and-pillar mines with lagging cave conditions, mining under massive stratigraphic units in Western U.S. mines.

Poster Session II::

PET-P-02: Tuesday, June 30, 2015, 03:30 pm - 04:30 pm

ARMA 15-0020

A finite element technique with triangular gird split method for hydraulic fracture propagation simulation in reservoirs

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The fracture propagation simulation is extensively studied analytically and numerically since the hydraulic fracturing is widely used for the exploitation of unconventional reservoir resources. Especially, the fracture propagation in natural fractured reservoirs often behaves twist and curved trajectories, so the fracture orientation and propagation path determination need more computational work in fracture tip stress field analysis in current finite element models. This paper describes a new finite element approach solving hydraulic fracture propagation by triangular gird split method (TMSM). This approach uses cross-correlation integral to compute the mix-mode (opening and sliding modes) stress intensity factors, and the vector cross-product is applied on the split element position. The arbitrary fracture propagation angle is obtained through the maximum tangential stress criterion. Thus, the crack dynamic propagation simulation can be achieved by the local unit of the crack tip through mesh split or node movement. Because the fracture can grow along the mesh boundary or split one element, so this approach allows the fracture propagation path without the initial pre-determined meshes control. In the cases of 2D classical fracture propagation and fracture interference analysis between adjacent fractures, the efficiency and accuracy of this approach was validated comparing the existing mesh reconstruction method. The results show that this approach can simulate fracture growth exactly at more complex stress circumstances with the advantage of no singular element construction and local mesh refinement at fracture tips. The relative computational efficiency makes this approach can be applied for better description of fracture propagation problems in complex naturally fractured reservoirs.

ARMA 15-0022

Numerical study of the influence of fluid viscosity on well bore spalling in drained fractured rock

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Fractures existing prior to, or induced by drilling play a determinant role in spalling and block detachment during the stages of fluid injection and withdrawal in quasi-brittle rocks (e.g., shale). The objective of this work is to model wellbore spalling during hydrocarbon extraction. The rock mass is modeled as a jointed continuum with POROFIS Finite Element program (Pouya, in preparation). The problem is treated in plane strain. Simulations are performed in three stages: excavation of a circular hole, fluid injection and fluid withdrawal. The first loading path simulated is purely mechanical: excavation followed by wellbore pressurization and pressure relaxation. The second loading path simulates the injection and withdrawal of a single-phase fluid in a porous rock (in which both the matrix and the joints are porous). Joint elements are assigned a damage model coupled to a failure criterion: this allows simulating fracture propagation and subsequent block detachment and spalling.

In the first section of the paper, parametric studies are presented to relate breakout size to wellbore diameter and joint spacing. First, Finite Elements modeling blocks are assumed to be elastic: it is verified that breakouts grow in the direction of least compression. Second, Drucker-Prager plasticity model is assigned to the Finite Elements to study the interaction between the accumulation of plastic deformation around the well and the growth of breakouts by spalling. Third, sensitivity analyses are conducted to examine the variations of pressure in the fractures during fluid injection or withdrawal, and the consequent stability of the near-wellbore zone. In the second section of the paper, a real geological site is modeled. The model is verified against in situ measures such as caliper data and wave velocities. The sensitivity of the model to mesh refinement and joint spacing is discussed in the last part of the paper. The numerical approach proposed in this work will be used to recommend wellbore operation modes so as to avoid excessive spalling and clogging.
Keywords: wellbore, spalling, breakout, Finite Element Method, joint element, injection, withdrawal

ARMA 15-0059

Experimental and numerical 2D analysis of hydraulic fracturing using high-power electric discharge

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Hydraulic fracturing operation is one of the well-known and casual operations after perforation in oil and gas wells especially in unconventional reservoirs. One novel idea might be high injection pressure to create a simple two wing hydraulic fracture; however, it results in consumption of a considerable amount of fluid and increases the risk of propagation into underground water sources.
The impact of those disadvantages made researchers to bring up novel methods to do the hydraulic fracturing operation by jointing new sciences in solid mechanics and fluid dynamics. One of the most important and novel methods in this area is hydro-pulse pressure fracturing which is a dynamic fracture propagation method in which of the excessive pressure is produced using an electrical discharge. In fact, unlike the traditional quasi static fracture propagation, this method has the advantage of creating a two wing planar hydraulic fracture because of its dynamic fracture propagation essence and is applicable even in the system of naturally fractured reservoirs. Creating multiple fractures is also possible in this method based on the power that is being used.
In this paper a numerical and experimental pulse power fracturing study in which the fracture propagation can be controlled in unconventional reservoirs is presented. The experimental setup of our project produce 1KJ energy during electric discharge and the excessive pressure rose up to more than 100 Kpsi, enough for crossing faults and natural fractures. Furthermore, this research group already runs several tests which were performed on cylindrical 15 cm length and 5 cm diameter Shale and Dolomite specimens. Results showed that it was observed that measured fracture propagation rate in this method was increase in the case of comparison with the conventional quasi static fracture propagation methods. Further field scale tests on this method are required to determine maximum fracture length.

ARMA 15-0070

XFEM-Based CZM for the Simulation of 3D Multiple-Stage Hydraulic Fracturing in Quasi-brittle Shale Formations

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The Cohesive Zone Model (CZM) engages the plastic zone and softening effects at the fracture tip in a quasi-brittle rock, e.g. shale, which concludes a more precise fracture geometry and pumping pressure compared to those from Linear Elastic Fracture Mechanics. Nevertheless, this model, namely planar CZM, assumes a predefined surface on which the fractures propagate and therefore, restricts the fracture propagation direction. Notably, this direction depends on the stress interactions between closely spaced fractures and can be acquired integrating CZM as the segmental contact interaction model with a fully coupled pore pressure-displacement, extended finite element model

(XFEM). This later model simulates the fracture initiation and propagation along an arbitrary, solution-dependent path.
In this work, using XFEM-based CZM in Abaqus, we modeled four-stage 3D hydraulic fracturing in a triple-layer, quasi-brittle shale formation including slit flow and poro-elasticity for fracture and matrix spaces, respectively. We implemented a new method to connect our model to the infinite surrounding rock layers by replacing the horizontal stress boundary conditions with infinite elements around the solution domain of interest. Moreover, we characterized the cohesive segments by refining the stiffness, fracture initiation stress, and energy release rate using three geometric and accuracy criteria. Furthermore, we partitioned only the stimulation region into multiple XFEM enrichment zones to simulate multiple-stage fracture propagation, reduce computational expenses, and avoid unrealistic fracture growths around sharp edges.
We demonstrated the significance of operational parameters, rock mechanical properties, and loaded or fixed boundary conditions in fracture aperture and propagation direction in sequential and simultaneous four-stage fracturing cases. Also, having compared the multiple-stage fracturing results from planar CZM with those from XFEM-based CZM, we found that the stress shadowing effect of hydraulic fractures on each other can cause these fractures to rationally propagate out of plane. We investigated the effect of this arbitrary propagation direction on not only the fractures' height, length, aperture, and the required injection pressure, but also fractures' connection to the wellbore. This connection can be disrupted due to the near-wellbore fracture closure which may embed proppant grains on the fracture wall, or screen out the fracture at early times.
Our results verified that the near-wellbore fracture closure strongly depends on three remarks: 1) the implemented model, planar or XFEM-based CZM; 2) the fracturing scenario, sequential or simultaneous; and 3) the fracture spacing. Ultimately, we proposed the best fracturing scenario and spacing to maintain the fractures connected to the wellbore for better proppant placement and subsequent production.

ARMA 15-0072
Evaluation techniques of wellbore stability on complex formation based on wettability

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Wettability is not only controlling factors of reservoir fluid distribution, but also greatly affects physical and chemical properties of rock, including capillary force, relative permeability, electrical properties and even strength. Especially before and after drilling formation, wettability has a more important influence on wellbore stability. In most previous literatures, unchanged wettability considered as a default premise, impact of wettability and its changes on the rock, thereby on wellbore stability was ignored.
In this paper, an oilfield in western China taken for example, from the viewpoint of wettability, wellbore instability mechanism under the condition of oil-based drilling fluid was studied. During the process, the core samples were investigated using X-ray diffraction (XRD) tests, water activity (Aw) tests, swelling ratio (sw) tests, dynamic wetting test, computerized tomography (CT) tests, Field Emission Scanning Electron Microscope (FE-SEM) tests and uniaxial compressive strength (UCS) tests.
The results indicate that wettability has a great influence on micrometer or even nanometer cracks, the stress accumulated by which is one of micro-cracks extension and growth, whereas traditional theory had ignored usually. According to the structure and composition of the cores and wettability changes resulted from the cores contacted with drilling fluid filtrates with different performance parameters, such as water activity et al, a comprehensive characterization model on the properties of rock and drilling fluid based on wettability was proposed to maintain the original strength of rock. The model above considered wettability was used as an effective solution to the problem that

wellbore instability occurred frequently even though density and conventional performances of oil based drilling fluid are within a reasonable range of projects.
The model will also provide a theoretical basis and technical support based on the wettability for designing performance properties of oil based drilling fluid.

ARMA 15-0103

Development of a Transient 3D Multilayered Geomechanic Hydraulic Fracture Model to Evaluate the Temporary Localized Change in Stress Anisotropy

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In order to properly evaluate the localized transient modifications in stress anisotropy during hydraulic fracturing operations, a novel transient 3-D hydraulic fracture model was developed. The new model incorporates cohesive zone elements to represent the fracture plane, including fracture initiation and dynamic propagation. Cohesive zone elements are a relatively common fracture model technique, as they eliminate the need to model the stress singularity at the fracture tip, and fracture extension is calculated from the fracture energy release rate of the rock formation, which for mode I fractures is driven by the relationship between the local tensile stress and the ultimate tensile strength. In order to capture the 3-D characteristics of the fracture growth, multiple rock layers were included in the model (see Figure 1). The material properties of each layer are specified independently, and the layers are coupled through friction interface elements. Pressurized rock testing was performed for various rock combinations to characterize the respective friction coefficients between the formation layers. The frictional elements allow for the fracture height to propagate into the bounding formation layers. When the fluid pressure is reduced on the open fracture, the fractional elements act as en energy storage mechanism to impede the instantaneous return of the formation to its original stress state, thus capturing the temporary localized change in stress anisotropy. Additional studies will focus on utilizing this temporary modification of the local stress anisotropy to enhance fracture treatments and improve post job production levels.
The current version of the model is soli a geomechanical representation of the hydraulic fracturing process. The relative permeability of the rock formation is assumed to be very small, making fluid leak-off negligible. The effect of the fluid on the fracture surface is therefore modeled through a simple fluid penetration algorithm. As fracture faces open they are exposed to a pre-defined net pressure value at that radial distance from the wellbore. Future version of the model aims to incorporate a fully-coupled fluid simulation, which would include fluid leak-off, proppant transport, and dynamically calculated net pressure distribution along the fracture geometry. Statistical variation in rock properties will also be added to better represent the uncertainty of the geomechanic environment. Additional improvements may also include the extension of the model to dynamically modify the direction of the fracture planes.

ARMA 15-0120

Modeling fluid-driven fractures using the generalized finite element method (GFEM)

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Hydraulic fracturing is a widely used technique in the oil and gas production to increase the permeability of near-well reservoir and enhance hydrocarbon recovery. Modeling hydraulic fracturing involves solving coupled multi-physics equations in a robust numerical solution scheme. We present a generalized finite element framework to simulate the propagation of fluid-driven fractures in a linear elastic medium. The fluid flow within the fracture is described by the Reynolds lubrication equation, where the classical cubic law links the fluid pressure gradient and the flow rate in the fracture plane. A so-called 'local U-P' formulation is developed to discretize the coupled pressurized-fracture system. The GFEM framework allows fractures to propagate inside the cells, and thus finite element discretization can be non-conforming with fracture geometry. Here the fracture propagation process is governed by the cohesive zone model. The fluid front is tracked to permit fluid lag during the simulations. A unified traction-separation law is proposed to model the mechanical behavior of the fracture faces, including contact, cohesion and interface strength softening. The traction-separation law on the fracture faces is enforced by a penalty method. A polynomial pressure projection (PPP) stabilization technique is used to stabilize both the fluid pressure and traction fields on the fracture faces. The coupled nonlinear system is solved by a standard Newton-Raphson method. Several 3D numerical studies and benchmarking examples will be presented to demonstrate the capability of the proposed framework in modeling fluid-driven fracture propagation.

ARMA 15-0258

Lattice bond cell modeling of dynamic hydraulic fracture

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The correlated lattice bond cell(CLBC) is a newly developed lattice model of rock for dynamic fracture(see *Zhang and Chen, Comput. Methods Appl. Mech. Engrg, 2014,279:325-347*). It represents a rock with a discrete structure composed of lattice bond cells. Each lattice bond cell can take any geometry with any number of bonds. The interactions between particles in a cell are characterized by the modified Stillinger-Weber potential, which makes the CLBC able to represent the variable Poisson's ratio. The micro physical parameters of bond potential are related to the macro mechanical constants of rock. For the CLBC has implicitly incorporated the dynamic fracture criteria into the constitutive model of bond cell through the bond potential, the CLBC can simulate the dynamic fracture initiation, propagation, branching and arresting behaviors without any separate criterion. This makes the CLBC highly efficient in dynamic fracture simulation in rock.
The hydraulic fracture is a very important technique to stimulate production of unconventional reservoir. However, how to simulate the hydraulic fracture, especially the dynamic hydraulic fracture, in a heterogeneous rock has been a big challenge. The hydraulic fracture is essentially dynamic since the high water pressure is applied to rock in a short time. To capture the fracture behavior more accurately, it is quite necessary to conduct the dynamic fracture simulation. However, the rock is a heterogeneous geo-material. Subjected to high water pressure, when and how the hydraulic fracture initiate, propagate and branch are very difficult problems for the continuum-mechanics based method. To avoid these difficulties, the CLBC is used to model the dynamic hydraulic fracture process in rock. In this work, a special technique is developed for the application of hydraulic pressure to numerical model and the identification of fracture trajectory. The branching behaviors of hydraulic fracture are analyzed. The correlations between the water pressure, injection rate and the characters of hydraulic fracture propagation and branching are analyzed. The robustness of simulation results with respect to meshing scheme is examined, which shows that the present method is insensitive to the meshing scheme. It is suggested that the present method is an effective method for dynamic hydraulic fracture simulation.

ARMA 15-0259

Wellbore stability of the sandstone formation buried in high pressure and high temperature considering radial porous media flows of a compressible gas

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On the one hand, under the combined effects of high temperature and pressure, the mechanical property of ultra-deep sandstone is significantly different from those of normal temperature and pressure. On the other hand, a high pressure gas is highly compressible near a wellbore where the gas pressure drops significantly to match the flowing pressure. They are responsible for wellbore instability of the sandstone formation in radial porous media flows of a compressible gas such as well

test and gas production. The purpose of this work is to experimental investigation on properties of ultra-deep sandstone and forecast wellbore stability of high pressure gas wells with open-hole completion during well test.

Triaxial tests are performed on sandstone of Tarim Basin's ultra-deep wells at high temperature and room temperature using GCTS RTR-1500 triaxial experimental system. Sandstone's full stress-strain curves under different experimental conditions are plotted, and a modified Duncun model with temperature term is proposed based on experiment and theory. Sandstone's elastic modulus and Poisson's ratio are calculated, and relations between the properties of sandstone and varying temperature are analyzed. A simple analytic treatment of compressible gas flow in porous media is used to analyze the gas flowing pressure distribution. Finally, wellbore stability model of ultra-deep sandstone formation in gas wells with open-hole completion during well test is proposed.

The results show that a modified Duncun model with temperature term can forecast the stress-strain curves of ultra-deep sandstone in different temperature. The temperature has a significant impact on elastic modulus of sandstone, but doesn't affect Poisson's ratio of sandstone. A field case verified that the proposed wellbore stability model could be applied to predict the test differential pressure of ultra-deep sandstone formation during well test.

This work will be of significantly importance to engineers during predict the test differential pressure of sandstone formation during well test, in particular for the sandstone formation buried in high pressure and high temperature.

ARMA 15-0329

Numerical Simulations of Fracture Curving Interaction of Two Fractures Research about regularity of fractures extending in multi-staged hydraulic fracturing treatment

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Abstract: Clusters perforations and multi-staged fracturing treatments in horizontal well are usually used in the development of unconventional oil and gas, for which several fractures can be initiated in one stage at one time. Fracture initiated and extended afterwards will probably connected to the established fracture in present stage or the former stage, causing deviation of the fracturing fluid flow channel, which leaves hydraulic fractures difficult to effectively spread and . In this paper, a finite element numerical simulation is made about the influence of fracture development on the formation stress field and extending orientation of other subsequent fracture. Thus, influential factors of the critical fractures' distance can be obtained in which multiple parallel fractures will not deflect or intersection both in the same segment and adjacent segment. The results show that a longer critical distance between fracture surfaces is needed when the adjacent fracture size increases. Meanwhile, the orientation of fracture is related to the relative extending speed, namely dynamic size-dependent. Based on above calculation, guidance is provided for optimization of fractures distribution and perforation clusters distance for multi-staged fracturing treatments.
Key words: Multi-staged fracturing; orientation of fractures; critical distance; fractures distribution;

ARMA 15-0388

NUMERICAL MODELING OF SINGLE-CUTTER TESTS IN CARBONATES

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The petroleum industry has shown great interest in study drilling optimization on pre-salt formations given the low rates of penetration observed so far. Rate of penetration is the key to economically drill the pre-salt carbonate rock. The paper presents the results of numerical modeling through finite element method and discrete element method for single cutter drilling in carbonate samples. The work is relevant to understand the mechanics of drill bit – rock interaction while drilling deep wells and the results were validated with experimental data raised under simulated

downhole conditions. The numerical models were carried out under different values of fluid pressure acting on the sample surface and different cutter chamfer configurations. The forces generated on the cutter are translated into mechanical specific energy, MSE as this parameter is often used to measure drilling efficiency. The results indicate there is a significant increase in drilling resistance with confining pressure and that it is larger than the increase in shear strength of the rock subjected to the same range of confinement. Results also show that the chamfer size does not change significantly the mechanical specific energy values, although the cutter aggressiveness is influenced by this geometrical characteristic. Experimental results, obtained from triaxial confining tests made in carbonate rocks, were used to calibrate numerical triaxial models. The results were used to create a virtual rock to be utilized by both the discrete and finite element methods. Finally, examples of satisfactory agreement between theoretical and experimental data are reported and discussed in this work.

ARMA 15-0398

Simulation of Particle Suspensions Using a Coupled Lattice Boltzmann and Discrete Element Method

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Transport of dense particle suspensions is of interest in a broad variety of industries from drug development to oil recovery. However the rheology of such suspensions is often characterised by semi-empirical models which lack the flexibility required to accurately capture the relevant phenomena.
Previous work in this field has focused on development of constitutive equations to describe the effective viscosity of suspensions with a specific solid volume fraction. The rheology specified by such expressions is then typically used to calibrate a power-law based rheological model. However, work by Lyon & Leal has shown that even in a relatively simple poiseuille flow the distribution of solid particulates is not uniform across the aperture. This spatially varying solid volume fraction brings into question the applicability of constitutive equations to fully describe suspension rheology.
Using a coupled lattice Boltzmann and discrete element method, we have developed a new tool for the numerical characterisation of dense suspension rheology. This approach has been implemented using a shared memory, multicore, parallel architecture which allows for rapid and inexpensive evaluation of model results. Where model capabilities include non-Newtonian rheology, turbulence, fluid-solid interactions, and lubricated solid-solid interactions. Through consideration of the fundamental phenomena of flow and contact mechanics this model is able to accurately capture the suspension rheology.
Using this coupled framework we have implemented a numerical couette flow rheometer, discrete element particles are packed into a cubic lattice Boltzmann domain which is periodic in the lateral directions. Using either stress or shear rate control, this model then simulates the shearing of the particulate suspension. The resultant hydrodynamic and mechanical forces on the shearing plane are recovered once the model has achieved a steady state, where these results are used to compute an effective suspension viscosity. The results from this analysis have been validated against existing semi-empirical expressions.

ARMA 15-0405

Correlations Between Acoustic Emission Microcrack Displacement Vectors and In Situ Stress Conditions During Laboratory Hydraulic Fracture Testing

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Laboratory hydraulic fracturing (HF) experiments were performed on multiple true triaxially confined prismatic granite specimens with samples sizes of 15 × 15 × 25 cm^3 and monitored with acoustic emission (AE) in order to simulate the field development of oil, gas and enhanced geothermal systems reservoirs. Ten millimeter diameter wells were stimulated using approximately

120 cP oil at flow rates of 0.1 mL/min through a non-perforated openhole. Pump pressure, wellhead pressure, pump flow, applied triaxial stresses and AE were monitored throughout testing. AE was monitored from more than ten observation locations and extensively analyzed post-test for source location, AE event attributes, and source mechanism characterization. Mode of failure of each individual microcrack was determined using AE moment tensor inversion techniques. Orientation and direction of crack displacement vector and crack face normal vectors were calculated from an eigenvector decomposition of the moment tensor solution and provided valuable information on how individual microcracks contribute to an image of the overall coalesced hydraulic fracture. Further analysis was performed to determine if trends existed between the boundary stress conditions and the crack vector information. Large numbers of events were observed to have similar microcrack displacement vector orientations, which were compared with principal stress directions as well as the maximum shear stress direction induced in the sample. Comparisons between crack slip vector orientations and mode of failure were also examined. The usefulness of the AE microcrack displacement vector information is apparent when some in situ stress conditions are unknown and an orientation of principal stresses is required.

KEY WORDS: Hydraulic Fracturing (HF), Acoustic Emission (AE), Moment Tensor Inversion, Granite, Laboratory

ARMA 15-0421

FDEM modelling of thermo-mechanical wellbore instabilities within shale formations

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In the oil and gas industry, the stability of wellbores is a long-standing issue which results in substantial yearly expenditures. In the presence of instabilities, drilling and production are impacted by several additional costs in the form of equipment losses, washouts, problematic logging and sidetracking. These problems are generally aggravated when drilling through shales due to its anisotropic geomechanical properties. From a rock mechanics point of view, a redistribution of the in-situ stress field occurs around the wellbore following the excavation process. If the redistributed stresses exceed the strength of the rock (in tension or in shear), fractures will develop, thus resulting in potential hole instability. Additional instability mechanisms may be caused by rock expansion or contraction in response to thermal exchange with drilling fluids. In recent years, analyses based on the hybrid finite-discrete element method (FDEM) have been shown to provide a realistic representation of rock mass deformation and fracturing processes. To date, the FDEM approach has successfully yielded qualitative and quantitative results for several practical rock engineering applications, yet it has lacked the ability to account for thermo-mechanical coupling. The objective of the current paper is to describe recent advances in thermo-mechanical modelling using FDEM, and its application to the analysis of damage development around wellbores in bedded rock formations. The numerical investigation focuses on the interaction between the fracture network generated during the excavation process and the thermal stresses arising due to the injection of a cooler fluid. A sensitivity analysis of the in-situ stress conditions and the temperature fields is carried out.

ARMA 15-0492

Experimental Evaluation of passive-Vibration Assisted Rotary Drilling (p-VARD) tool to enhance Drilling performance

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Vibration Assisted Rotary Drilling (VARD) provides higher penetration rates with the potential of greater economic values in drilling, provided Non Penetration Time (NPT) is not excessive. The “p-VARD” tool with Poly-crystalline Diamond (PDC) cutters was developed to enhance drilling

performance by modulating the rock-bit interactions. Two prototypes were tested, one for laboratory use and another for field applications. The lab scale prototype was used for tests on synthetic rock specimens (concrete) with an Unconfined Compressive Strength (UCS) of ~ 40 MPa. Higher penetration rates with vibration were observed using the p-VARD tool, in comparison to tests without vibration. For the field trial a down-hole sensor sub was utilized to record axial vibrations generated during the process of drilling, and a site was selected consisting of separate layers of gray and red shale with an average strength of around 70 Mpa. Rock samples were collected and point load indices tests were performed to estimate the rock strength. Three wells were drilled up to a depth of 400 ft, 403.5 ft and 241.56 ft respectively, 20ft apart to ensure similar formations. A significantly higher Rate Of Penetration (ROP) was recorded using the p-VARD tool over conventional drilling. In addition to similar formation types in related tests and depths, drilling fluid (water) flow rates were as similar and constant as possible. Drilling results were evaluated on the basis of ROP, mechanical specific energy (MSE), bit loads (WOB) and bit displacements. In addition to improving drilling performance, the VARD technology used assists in eliminating stick-slip.

Key words: p-VARD, NPT, PDC, Point load index, ROP, UCS, Rock strength, Drilling performance, Synthetic rock, BHA and Weight On Bit (WOB).

ARMA 15-0518

A new prediction model of energy consumption on rock fragmentation and rate of penetration based on the fractal theory

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One of the major challenges during drilling in hard-brittle formation in Tarim basin is to evaluate the rock drillability and to predict the rate of penetration (ROP) accurately. Currently, many investigators have evaluated the drilling resistance of rock and predicted the ROP mainly from the perspective of rock drillability and drilling rate equation, which increases drilling cost and reduces the predictive reliability of ROP. Consequently, the aim of this article is to analyze the drilling resistance of rock and to predict ROP from a new angle.

In this paper, the fractal characteristic of rock fragmentation and the problem of rock energy consumption in drilling process are studied based on the fractal theory through rock-breaking laboratory experiment by roller cone bit and rock cuttings screening experiment. A new prediction model of energy consumption on rock fragmentation is proposed based on size distribution of rock cuttings, fractal dimensions, and energy dissipation analysis. Also, the prediction equation of ROP is given based on the principle of conservation of energy. The biggest advantage of this model is that the energy consumption on rock fragmentation and the ROP can be predicted entirely based on rock cuttings, fractal dimensions and drilling parameters. Moreover, it can be measured while drilling (MWD).

According to field data analysis, the consistency, between theoretical prediction value and field<s>
</s>data, is encouraging, with an average error below 10%.

It is believed that this model, based on the fractal theory, provides a new idea and method for optimizing drilling parameters and improving drilling efficiency.

ARMA 15-0530

Finite Element Modeling of Curving Hydraulic Fractures and Near- Wellbore Hydraulic Fracture Complexit

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An outstanding question in the design of a hydraulic fracturing treatment is how fractures, which often initiate in 'non-ideal' orientations under the influence of near-field stress concentrations, propagate outwards and turn towards their ideal orientations under the far-field stress conditions.

Using a fully coupled 2D/3D Finite Element hydraulic fracturing model in GEOS, we simulate fracture initiation and propagation for three distinct cases: First, we consider the growth of a simple bowl shaped fracture near a free surface. The numerical results are compared against recently published experimental results and are used to calibrate the model response. Second, we consider the growth of an infinitely long axial fracture from a vertical wellbore for a range of stress states, fracture orientations, and fluid characteristics. Finally, we consider the case where a discrete axial fracture from a horizontal wellbore propagates outward and transitions to a transverse fracture.

ARMA 15-0541

Stress path of coal seams during depletion: the effect of desorption on coal failure

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Unmineable coal seams constitute important domestic sources of natural gas in several countries including Australia, USA, Canada, and China. Coal seams differ from conventional reservoirs in the sense that they constitute the source and reservoir rock at the same time. Although limited in size, coal seams have the advantage of being naturally fractured, which facilitates drainage upon depletion.

Reservoir depletion changes the state of stresses in the reservoir and nearby formations. Field data from coal seam gas production documents order-of-magnitude increases of permeability upon depletion which sometimes is followed by significant fines production, termed as "coal failure". In fact, coal seams are unique in the sense that additional changes of strains and stress are expected during depletion because of desorption-induced shrinkage.

We performed experiments replicating the stress path of coal seams far from the wellbore considering in-situ vertical stress larger than horizontal stress, no change of lateral strain and constant total vertical stress. Experimental results show that desorption-induced shrinkage promotes significant lateral stress relaxation sometimes leading to shear failure. Experimental results are supported by a poromechanical model of the coal seam which includes adsorption effects on the coal matrix. The poromechanical model considers a doble porosity system composed by natural fractures in coal seams and micro/mesopores in the coal matrix.

Laboratory experiments and theoretical modeling support the hypothesis that desorption of gas from the coal matrix can lead to pervasive shear failure in coal seams wherever desorption is significant. Desorption amplifies the effect of pore pressure reduction and makes shear fracture reactivation more likely to happen than in non-sorbing rocks. This study shows the importance of considering depletion in coal seams as a chemo-geomechanical coupled process.

ARMA 15-0665

ADrilling through highly faulted / fractured zones: Case study, an integral approach with successful results

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Many of the oil fields onshore southern Mexico are characterized by complex geology in both Tertiary and Mesozoic sediments. This requires the drilling of high-complexity wells through highly faulted and fractured zones, overpressured sections and depleted reservoirs. The presence of tight hole, torque and drag, excessive cavings production and stuck pipe events are typical. Therefore, the drilling process in fraught with NPT due to additional wiper trips, excessive reaming and back

reaming operations, stuck pipe events, and undesirable side tracks with a high impact on the final operation costs.
This paper presents a field case where a well was drilled in a very highly fractured and faulted zone. After drilling to 4500 meters md and pulling out of hole to do a wiper trip, it was very difficult to reach the bottom hole due to high torques, tight hole events and stuck pipe attempts, in the interval from 4000 to 4300 meters md. The NPT due to wellbore instability issues was of 182 hours with an operational cost of USD 132,000 and a high potential of needing to execute a sidetrack.
A 1-dimensional Mechanical Earth Model was built, followed up with Logging While Drilling measurements, cavings morphology monitoring and 3D caliper analysis. This geomechanics analysis identified the main failure mechanism as planes of weakness. It was therefore recommended to maintain the mud density and improve the sealing capacity of mud to reduce the invasion and pressure diffusion into the fractured shale.
After mitigation measures were implemented it was possible to run in hole up to 4500 meters md and continue drilling up to the 7" casing point at 5250 meters md. Logs were later run, showing an in-gauge wellbore from 4500 meters md to the bottom of the hole. This indicates the effectiveness of proper mitigation measures, avoiding continued mechanical degradation of the stability condition in the overlying section and avoiding an undesirable side track.

ARMA 15-0751
Borehole stability analysis using results from full field reservoir geomechanical simulation: a CBM case history
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Single or multilateral horizontals wellbores are preferred to maximize reservoir contact in deep, single seam coalbed methane (CBM) reservoirs. If a section of the wellbore collapses/fails due to geomechanical issues, the wellbore production length is decreased. The resulting collapse will create coal fines which can plug the well and also clog and damage downhole pumps, and the well shut down for recompletion, workover, and/or downhole pump change. During this downtime gas production/revenue is lost. Additionally, the reservoir will repressurize, and additional time after the workover/pump change will be required to achieve a producible state. Therefore, the stability of the wellbores is a primary concern when maximizing well productivity.
In this study, a hydro-geomechanical coalbed methane reservoir characterization workflow is applied to multiple multilateral wellbore stability cases from the same coalseam formation. The data from core studies and borehole geophysical logging is integrated to create full field hydro-mechanical earth models. These models are then used for sequentially coupled reservoir geomechanical simulation. The coupled simulations results are history matched against observed gas and water production rates. The initial and evolved stress tensor from the simulation is used to provide insight into observed horizontal CBM wellbore stability issues including borehole: azimuths, well paths, side tracking, fines generation, and failure during depletion.

ARMA 15-0764
Cuttings Analysis for Rotary Drilling Penetration Mechanisms and Performance Evaluation
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Rock-bit interaction models are well known for PDC bits and percussive drilling as well as the relationship between these penetration mechanisms and characteristics of cuttings. This paper describes the correlation of cuttings analysis with the performance of a passive Vibration Assisted Rotary Drilling (p-VARD) tool developed by the Advanced Drilling Technology group of Memorial University of Newfoundland. This tool utilizes rock bit interactions to create axial vibrations in order to improve rock penetration. Laboratory testing of this tool showed an enhancement in the penetration mechanism which led us to expect that the use of pVARD with

conventional bits represents a change in the rock-bit interaction model. In order to investigate this change, and to understand the effect of pVARD tool on the drilling process in general, one-week field trials were conducted at the Red Bridge Road Quarry in Newfoundland in September 2014. Multiple wells were drilled to an average depth of 400 feet while performance parameters where measured. The Rate of penetration (ROP) was increased with the use of pVARD tool, consistent with the findings in the laboratory. In addition to drilling performance parameters, more than 140 cuttings samples, from the various formations encountered, were collected on intervals ranging from 5 to 20 feet. Subsequent laboratory analysis such as particle size distribution was performed for these samples, sieving according to an ASTM standard for soils, slightly modified for rocks cuttings. In addition, complementary analyses were performed on the cuttings for mineralogy and clay content to determine the relationships with drilling parameters like ROP, rock strength, and bit type. Higher ROP and better drilling performance parameters were observed for a higher coarseness index in a given formation. The use of a PDC bit with the pVARD tool had an effect on the grading of the cutting samples. These relations were very significant for a rock bit interaction model that describes the penetration mechanism of PDC bit with the use of the pVARD tool.

Key words: Rock-bit interaction, pVARD, ROP, Particle size distribution, coarseness index, PDC, grading.

ARMA 15-0771

Effect of Frac Fluid Temperature on Post Frac Gas Production

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The first hydraulic fracturing was implemented in conventional reservoirs. However, this technology was not applied to Unconventional resources such as Shale reservoirs until recently. As a result of its application, along with the advances in design of the environmentally acceptable fracturing fluid, we are witnessing a remarkable increase in production of oil and gas in US. In this work, we show our experimental and theoretical related to heating the frac fluid by a few degrees for increasing gas production even more.

To address the issue of the increased gas production from shale through shortening the post-frac shut-in time, we have studied and experimented with Pierre shale in detail. In our experimental work we suspended few grams of the shale samples in heated, de-ionized water and measured the changes in pH, E_h, (Redox potential), and Temperature. Using a video recording system, we simultaneously recorded the process of gas bubble flow under the microscope. We plotted our 2^{10} data points. We used the Fourier Transform of the raw data to construct a Power Spectrum which we use to extract the hidden information from frequency domain.

The results are: 1. it takes a short characteristic time for the heated water molecules to saturate and activate the shale capillaries. This part of the plot of E_h Vs Time shows that at the beginning of the experiment the capillary saturation and activation is controlled by the heat of the fluid. The dominating frequency associated with this stage is the mean frequency. At the end of this process a Diffusive transport of the heated water into the shale mass begins. This section follows the Fick's second law of diffusion. Diffusion process; using heated water instead of cold water, is much faster and 2. The E_h show the release of the *first gas bubble* to be the result of diffusion of the heated water in the shale capillaries where a small amount of *energy* displaces the sorbed gas from the shale micro pores. Interestingly, the gas production mechanism follows the predictable Activation Energy accurately as described by Arrhenius equations and when combined with Diffusion equation.

We conclude that (a) the diffusion time and the flux rate of water molecules into the shale capillaries can be shortened. We may estimate the optimal post frac shut-in time and monitor the advance of frac water displacement into the walls of the main hydraulic fracture. Achieving higher gas production can be realized through faster Capillary Saturation/Activation by heated water and (b) the desorbed gas production follows a pulsing, swarm flow.

The practical application of the simple technology suggested in this paper is (1) we propose a cost effective methodology for determining the post frac optimal shut-in time which is much shorter than that of shut-in time when compared with cold water, and (2) once this optimal shut-in time is implemented the industry may benefit from realizing quicker and higher gas production from their prospects.

ARMA 15-0786

Hydraulic Fracturing in Shale with H_2O, CO_2 and N_2

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Slick-water fracturing is the most routine form of well stimulation in shales, however N_2, LPG and CO_2 have all been used as "exotic" stimulants in various hydrocarbon reservoirs. We explore the use of these gases as stimulants on Green River shale to compare the form and behavior of fractures in shale driven by different gas compositions and states and indexed by breakdown pressure and resulting morphology of the fracture networks. Fracturing is completed on cylindrical samples containing a single blind axial borehole under simple triaxial conditions ($\sigma_1 > \sigma_2 = \sigma_3$). Results show that: 1) under the same stress conditions, CO_2 returns the highest breakdown pressure, followed by N_2, and with H_2O exhibiting the lowest breakdown pressure; 2) CO_2 fracturing, compared to other fracturing fluids, creates the most complex fracturing patterns as well as the coarsest fracture surface and with the greatest apparent local damage; 3) under conditions of constant injection rate, the CO_2 pressure build-up record exhibits condensation between ~5-7*MPa* and transits from gas to liquid through a mixed-phase region rather than directly as for H_2O and N_2 which do not; 4) there is a positive correlation between minimum principal stress and breakdown pressure for failure both by transverse fracturing (σ_3 *axial*) and by longitudinal fracturing (σ_3 *radial*) for each fracturing fluid with CO_2 having the highest correlation coefficient/slope and lowest for H_2O. We explain these results due to correlations with the specific properties of the stimulating fluids.

ARMA 15-0816

Increasing the Pierre Shale Reservoir Volume Using Heat- Part I

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Hydraulic Fracturing is a technique to stimulate the production of hydrocarbons from a well by injecting high pressure fluids. Hydraulic Fracturing uses large amounts of chemicals and relatively *cold* freshwater to create enough fluid pressure to overcome the cementation and the overlying rock stresses. Pierre shale, the subject of our study, is very soft and possesses a high concentration of swelling clay, so it may be possible, as described below, to fracture a Pierre shale formation by using heat. This method may in fact be cheaper and more environmentally friendly than traditional hydraulic fracturing methods if medium to low quality steam is used. Use of heat requires documentation of Pierre shale thermodynamic properties. Therefore, an experiment was designed to find the thermodynamic and the associated strain properties of Pierre shale exposed to heat. First, samples of shale were cut, weighed, measured, and were sprayed on with a random pattern of paint particles for digital image correlation. Samples of Pierre shale were heated on a hot plate while a

VIC-2D strain camera observed the heated sample and VIC-2D software calculated the strain in the x and y directions across a face of the sample using changes in the digital images.
The results of analysis of data showed that that sample contracted in the x direction and expanded in the y direction. The strain data graph shows oscillations in the sample as it is subjected to heat. Additionally we have calculated the Poisson's ratio of Pierre shale subjected to the heat load. Furthermore, it is possible to find the resonance frequencies of the various layers of the shale, and thus find the resonance points along the axis of horizontal well.
The hypothesis introduced in this paper is that if the frequency of the shale is matched by a calculated external or forcing frequency at the resonance points, it is possible to generate micro fractures in the shale in the horizontal section of the hole. This is expected to increase the reservoir volume economically. Furthermore, the strain data shows that heat waves can be seen by changes in strain axially. Further studies will calculate the resonance frequency levels of Pierre shale, and the temperatures needed to generate the frequencies which affect the strain.

INT-P-02:

Tuesday, June 30, 2015, 03:30 pm - 04:30 pm

ARMA 15-0135

Proppant transport and settling in a narrow vertical wedge-shaped fracture.

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An appropriate fracture propping is important for oil and gas production (especially in shale formations). The actual proppant placement during fracturing is generally unknown. Any fair prediction of the placement of proppant results in significant improvements for the fracture design. Although modeling tools exist, there are still uncertainties regarding the extent to which such approaches can predict the real packing of proppant in a fracture.
We compare experimental data with simulations of the same scaled fracture and study the transport and settling of particles suspended in a viscous Newtonian fluid that passes through a narrow wedge-shaped vertical fracture. We report the dynamics of the particle deposition as a function of the flow rate. We also consider the evolution of the pressure drop as the cell is packed with particles.
The experimental cell has transparent walls that allow for direct video recording of the process. Modeling is done via a one-way Euler-Lagrange CFD-DEM simulation. Particle-particle and particle-wall interactions include damped Hertzian contact forces in the normal direction and Coulomb friction in the tangential direction. In the simulations we measure the density profile of the settled dune and consider the effect of the flow rate and particle-fluid density mismatch.
We compare the experimental and modeling results for the final particle placement after a steady dune is formed. We also discuss the ability of the one-way coupling to yield qualitative agreement with the experiments.

ARMA 15-0367

Fundamental investigation of gas injection in microfluidic shale fracture networks at geologic conditions

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Micromodels are thin porous structures in which flow is restricted to two-dimensions and in recent years they have proven to be effective tools for visualizing and quantifying complex flow and transport phenomena. In this work, we describe a unique micromodel experimental system that consists of a pressure chamber equipped with a sapphire window through which experiments are imaged using fluorescent microscopy. The pressure chamber allows us to conduct experiments at

geologically relevant conditions with a maximum working pressure and temperature of 1500 psig and 80 ˚C, respectively. These conditions make it possible to use supercritical carbon dioxide (scCO2) as a working fluid, which is relevant to CO_2 sequestration, hydraulic fracturing, and enhanced oil and gas recovery operations. We fabricate our micromodels in engineered materials such as glass or silicon, as well as in geomaterials (e.g. shale, siltstone, and Portland cement). We will present experimental results in simple fracture systems (e.g., straight channels, fracture doublets) with applications to hydrocarbon mobility in hydraulically fractured shale. We use both shale and glass micromodels, allowing for a detailed comparison between flow phenomena in different materials. In these simple systems, we investigate oil trapping, mobilization, and interfacial velocity. Next, we will present experimental results in complex fracture network patterns derived from 3D x-ray tomography images of fractures in shale rock cores. In these fracture networks we focus on sweep efficiency using water, nitrogen, and $scCO_2$ as injection fluids. We will discuss the effectiveness of each fluid and present analysis aimed at developing quantitative relationships between fluid mobility and interfacial phenomena.

ARMA 15-0463

Multiscale characterization of physical, chemical, and mechanical heterogeneity of mudstones

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Multiscale characterization of anisotropic, heterogeneous pore structure and compositional (e.g., kerogen, clay, cement, etc) distribution from nano- to deci-meter scales profoundly influence the thermo- hydro- mechanical- chemical response of shale materials during stimulation and production. A high fraction of shale pore volume can reside in pore networks on the order of <10 nm size, which is also relevant for shale/clay yield, failure, and matric potential effects. We investigate the impact of these lithologic heterogeneities on physical, chemical, and mechanical properties across a wide range of scales for a common lithofacies of Cretaceous Mancos Shale. Multiscale characterization of shale samples from a micron to core scale will be integrated. Core samples will be identified based on principal macroscopic lithofacies which will be examined petrographically. Thin sections impregnated with fluorochromes will be examined using laser scanning confocal microscopy (LSCM) to characterize micro-facies (i.e., geomaterial texture patterns) and mineralogy at micron- and sub-micron scales. X-ray fluorescence will be used to identify the mineralogical distribution at the thin section scale. Advanced multiscale image analysis for texture classification will be used to identify key features (or faces) of samples using dual focused ion beam-scanning electron microscopy (FIB-SEM), aberration corrected-scanning transmission EM (AC-STEM) and energy dispersive X-ray spectrometry (EDS). Integrated multiscale imaging techniques will be used to map the abundance, size, and spatial distribution of pore structure, kerogen, and mineralogy. Finally, multiscale 3-D image stacks will be segmented to rigorously test the scale of a representative elementary volume based on multiple measures from image analysis and pore-scale simulations. This characterization will be examined against experimental data including acoustic emission (Vp, Vs) and nano-indentation measurements of elastic properties using focused ion-beam milled pillars.

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ARMA 15-0557

A Newly Developed Centrifuge Testing Program of SAGD Caprock Integrity

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Following the unexpected caprock failure in Total's Joslyn Creek Steam Assisted Gravity Drainage (SAGD) project in 2006, the crucial importance of caprock integrity for safe operation of SAGD has been realized. In the past, most of the research efforts have been devoted to reservoir-geomechanical simulation studies of caprock integrity. Physical modeling is conducted to a lesser extent as it is difficult to carry out physical modeling of prototypes at such a scale as SAGD projects. With the newly-built 50g-ton beam centrifuge at Geomechanical Reservoir Experimental Facility (GeoREF), a pioneering work is ongoing to employ this powerful tool for physical modeling studies of caprock failure mechanism at high gravitational field. The centrifuge model will be spun at 100g. According to the scaling law, a 20m thick caprock formation could be simulated using only 20cm thick test material, which makes indoor physical modeling of caprock failure feasible.

In this study, prototype, reservoir-geomechanical simulations and centrifuge physical modeling are closely integrated. In reservoir-geomechanical simulations, caprock behavior is described using elasto-perfectly plastic model with Mohr-Coulomb failure criterion. The development of shearing zones in caprock is thoroughly analyzed in conjunction with the displacement evolutions at the bottom of caprock. According to the parametric studies, shearing patterns of caprock at failure are quite the same with the vertical displacement at the bottom of caprock being the main driving force. In addition, the vertical displacement profiles also share the same characteristics.

Based on the findings from the reservoir-geomechanical simulation, a custom-designed electric-mechanical device named Geomechanical Caprock Deflection Mechanism (GeoCDM) is built to implement such vertical displacement profiles at the bottom of caprock in the centrifuge model. The main components of GeoCDM are two sets of worm gears and one Parker servo motor. This device has been thoroughly tested at 1g and 100g environments for displacement and velocity calibration and lifting capacity verification. The testing results demonstrate that the GeoCDM is well designed and manufactured and can live up to the design expectations.

Currently, over-consolidated Speswhite kaolin with consistent properties is employed to mimic the caprock in the centrifuge model for the purpose of eliminating the influence of heterogeneity of in-situ materials. Through an image-based displacement measurement technique, the deformation of caprock under the influence of oilsands reservoir expansion is directly observed. For the first time, the full process of shearing zone development in caprock is captured which can significantly enhance the understandings of the caprock failure mechanism in SAGD process and further on contribute to the safe operation of SAGD projects.

ARMA 15-0247

Reliability analysis of rock slopes involving correlated non-normal variables using point estimate methods

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This paper reveals that how uncertainties can be taken into consideration when stability of a geotechnical structure is analyzed; thus, an example of a rock slope is chosen in which some random parameters are might be correlated or have non-normal distributions. Probabilistic stability analysis of the rock slope, is carried out utilizing the point estimate methods (PEM). The primary point estimate method which was proposed by Rosenblueth (1975), has been commented over time (e.g. Zhou & Nowak (1988), Harr (1989) and Hong (1998)) in order to be improved. It is indicated that when random variables are not normally distributed or there exist correlation among some of them, the Harr's and the Hong's PEMs are not capable to give precise results. As a result, this study aims to address an important issue that is associated with these alternatives in respect of asymmetry and correlation of random variables. In addition, it is tried to clarify impediments and superiorities of aforementioned PEMs with respect to applicability, efficiency and accuracy.
After presenting an overview of the above mentioned PEMs, illustrative example is indicated considering two cases. Firstly, it is assumed that random parameters are uncorrelated but they might

have arbitrary distributions; hence, different distributions are considered for non-normal variables. Secondly, correlation is also interfered in analyses allocating a range of quantities to the correlation coefficients following two purposes: a) assessing the accuracy and efficiency of the manipulated PEMs (i.e. the Harr's and the Hong's PEMs), b) finding out the effects of correlation coefficient variation on probability of failure.
A primary comparison among the results demonstrates that the modified Harr's and the modified Hong's PEMs calculate the probability of failure very close to the other PEMs. The importance of this understanding is better understood when the amount of computation effort which is required by each method is noted. For instance, in the discussed problem, contains five random variables, using the Hong's PEM rather than the Rosenblueth's or the Zhou & Nowak's PEMs, decreases the amount of simulations to approximately one third or one fifth, respectively. Also, analyses clear that increase in the amount of correlation which there exist among random variables, corresponds to decrease in probability of failure meaning disregarding the correlation coefficient results a more conservative design. In order to determine the amount of accuracy that is achieved by each method, the results of the MCS are selected as exact solution. It is discovered that the Rosenblueth's PEM has the minimum accuracy. Furthermore, it is indicated that although the Hong's PEM is able to consider more than two realization points for each random variables, sometimes it is not applicable due to unrealistic values that are calculated for realization points. Likewise, when number of random variables are large, the Rsenblueth's or the Zhou & Nowak's PEMs can be infeasible also the Harr's PEM might be inaccurate because it considers the realization points further from the mean.
Keyword
Uncertainty, Probabilistic analysis, Monte Carlo Simulation, Point Estimate Method, Probability of failure, reliability index.

ARMA 15-0324

Dual-scale modeling of time-dependent damage evolution and failure process of brittle rocks

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Excavation of an opening will alter the distribution of in situ stresses of the surrounding rock mass and macro- and micro-fracturing will occur in the Excavation Disturbed/ Damage Zone (EDZ). The EDZ can significantly alert the mechanical and hydraulic properties of rock mass such as strength, deformability, and permeability. Understanding the evolution of EDZ, in particular, the time-dependent development of EDZ is of great importance and has a vital role in the design and construction of rock engineering. To produce the time-dependent behavior of rocks, most of the previous models were developed by the superposition of several viscous and elastic elements or the empirically observed internal variables. Such phenomenological approaches do not accommodate the inherent physical mechanisms related to the time-dependent behavior of rocks and they are not adequate to capture the time-dependent fracturing process around an opening. Therefore, in this study a physically-motivated dual-scale modeling approach is proposed to model the time-dependent damage, deformation and fracturing behavior of rocks. The proposed model uses a microcrack-based damage constitutive law established at the elemental scale, in which the time-dependent degradation of elastic stiffness and damage-induced anisotropy are directly linked to microcrack growth. The key feature of the proposed model is to establish an adequate prediction of macroscopic creep behavior based on the microscopic kinetics of microcrack growth. The general capabilities of the proposed model are firstly illustrated with numerical simulations of biaxial creep tests. Then, the proposed model is employed to simulate the time-dependent evolution of EDZ around an opening and the effects of initial stress, excavation shapes and rock structures are investigated systematically. The present model provides an attractive virtual experimental tool to probe process-based understanding of complex time-dependent behaviors related to structures in geologic media.

ARMA 15-0535

DEM simulation of fracture process of inherently anisotropic rock under Brazilian test condition

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Fracture process of inherently anisotropic rock disc under Brazilian test conditions are investigated with the use of two-dimensional Discrete Element Methods (DEM). In the DEM model, the rock matrix is represented as an assembly of rigid particles bonded at their contacts and the presence of intrinsic anisotropy is explicitly modeled by imposing individual smooth joint contacts into the bonded-particle model. A series of anisotropic models with different angles between weak layers and loading direction are tested (β =0°, 15°, 30°, 45°, 60°, 75°, 90°). The anisotropic numerical model is firstly calibrated to match the variation of Brazilian tensile strength with anisotropy angles of anisotropic rocks from published experimental data (Vervoort et al., 2014). Good agreement can be found between the failure patterns of numerical model and those observed in laboratory. After that, the fracture process of anisotropic rock under diametrical compression is investigated in detail by exploring the occurrence, development and coalescence of micro cracks with different anisotropy angles. Micromechanical studies are also conducted by examining the modes, increment and orientation distribution of micro cracks at different stages in order to gain insights on the failure mechanisms of anisotropic rock under indirect tensile test conditions with different anisotropy angles.

Keywords: discrete element method; anisotropic rock; failure process; Brazilian test
Vervoort, A., Min, K.-B., Konietzky, H., Cho, J.-W., Debecker, B., Dinh, Q.-D., Frühwirt, T., and Tavallali, A., 2014, Failure of transversely isotropic rock under Brazilian test conditions: International Journal of Rock Mechanics and Mining Sciences, v. 70, p. 343-352.

ARMA 15-0675

Numerical study of cracking process using a new contact model

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Researchers have used the bonded particle model (BPM) to simulate the cracking process of rocks; but these simulations are mainly two dimensional although the cracking process is three dimensional. In this paper, the three dimensional BPM with a newly developed contact model which can properly consider the contribution of moments to contact normal and shear stresses and the condition at which the contact bond fails was used to investigate the cracking process of rocks containing a single flaw and under uniaxial compression. The new contact model which has already been implemented in PFC3D was first used to simulate the experimental cracking process of gypsum and Carrara marble containing pre-existing single flaws at different inclination angles. For comparison, the default PFC3D contact model was also used to simulate the experimental cracking process. Finally the influence of flaw shape (length and thickness) on the cracking process was systematically studied and the key features were identified based on the simulations. The results indicate that new contact model can predict the experimental cracking process very well, i.e., the first cracks (usually called primary cracks) initiate from the boundary of the pre-existing flaw and are always caused by tensile failure, and the secondary cracks first emanate from the tips of the pre-existing flaw due to shear failure and then develop to a mixed shear and tensile cracking zone. However, the default PFC3D contact model cannot simulate the observed cracking process.

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ARMA 15-0781

Geomechanical rock mass characterization with Terrestrial Laser Scanning and UAV.

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[1]*IMAGEO*

Thanks to the improvement of surveying equipment and data processing software, an increasing use of TLS (Terrestrial Laser Scanning) for investigating and monitoring rock cliffs has been made during the last decade.
Both scanning speed and operational range have been significantly increased, reducing the surveying time and increasing the extension of the study areas.
More recently, professional UAVs (Unmanned Aerial Vehicles) equipped with optical and thermal cameras as well as laser scanners became available, making it possible to integrate TLS and UAV data into a unique 3D software environment, reducing shadow areas and providing very detailed 3D models of inaccessible rock cliffs.

By applying proper software packages, it's now possible to extract not only the attitude of rock mass discontinuity surfaces directly from the point cloud, but also to map the distribution of significant parameters influencing the behavior of the rock mass, e.g. discontinuity spacing, fracture density, P21, URV, etc. Moreover, the possibility of draping high-resolution digital images over either a point cloud or a 3D mesh derived from it enhances the resolution of the 3D model and the capability of extracting geometrical information from the surveyed surface.
A workflow based on the use of both commercial software and properly developed GIS tools aimed at producing 2D and 3D maps with the distribution of significant parameters relevant to rock mass classification will be described. As an example, a map with the distribution of URV values aimed at supporting the design of slope protection works.

Selected case studies regarding rockfall hazard mapping in the Italian Alps will be presented.

ARMA 15-0674

Acoustic Monitoring of Mineral Precipitation in a Fracture

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Compressional and shear waves propagated across single fractures are sensitive to the size and distributions of voids and contact area in a fracture. The complexity of this fracture topology is captured by fracture specific stiffness which is an effective parameter that captures the deformed state of a fracture topology under stress. Fracture geometry can also be altered through geochemical reactions between pore fluids and the host rock. For example, mineral precipitation decreases fracture aperture and increases contact area between fracture surfaces. In this study, we examined the effect of mineral precipitation in a fracture on compressional wave transmission.
Transparent casts of a single induced-fracture in Austin Chalk were used to study wave propagation across a fracture prior to, during and after mineral precipitation. Transparent samples (100 mm by 100 mm by 50 mm) were used to enable direct visualization of mineral precipitation as a function of time. Precipitation of calcium carbonate ($CaCO_3$) was induced along the fracture plane through the mixing of two solutions: $CaCl_2$ + H_2O and $NaHCO_3$ + NaCl + H_2O. The two solutions were introduced through two separate ports using a dual-syringe pump (constant flow rate) to enable mixing that was controlled by the fracture void geometry. Two arrays with water-coupled compressional wave piezoelectric transducers (central frequency 1 MHz) were used to send and receive signals.
Mineral precipitation along the fracture plane was not uniform after flowing both solutions through the fracture for 100 minutes. Examples of the transmitted compressional wave are shown in Figure 1*center*. Transducer T2 was located in the region of minor precipitation while transducer T7 was located in a region with heavy and minor precipitation. While T2 probed a region that showed only minor precipitation, the transmitted signals exhibited an increase in amplitude compared to the signal from the water-saturated case ($t = 0$), while the signal from T7 decreased though mineral precipitation was heavy in the region probed by T7. Spectral analysis showed constructive and destructive interference caused by the non-uniform distribution of mineral precipitation in the regions probed. The wave interference results from scattering caused by the variation in the amount and spatial distribution of the precipitation. The detection of mineral precipitation within a fracture is possible by understanding wave interference and dispersion observed in the waveforms.

ARMA 15-0066

An Analytical Boundary Condition for D3Q19 Lattice Boltzmann Model

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Over the last two decades, the lattice Boltzmann method (LBM) has been emerging as an important computational fluid dynamics (CFD) technique for modeling fluid physics, especially when interfacial dynamics and complex boundaries are involved, such as the multiphase fluid flow in reservoir formation and fluid solid interaction in sand production.
Unlike the direct discretization of Navier-Stokes equations in the traditional CFD approaches such as FDM and FEM, in LBM packets of fluid particles move across the lattice following simple but special kinetic rules at the mesoscale such that the relations among macroscopic variables of fluids automatically recover Navier-Stokes equations. The mesoscopic kinetic nature of LBM brings many advantages over the conventional CFD methods, such as simplicity of the implementation, capacity of handling complex physical mechanisms, ease of parallelization, etc. On the other hand, the mesoscopic nature of LBM makes it awkward to implement boundary conditions. In traditional continuum-based CFD methods, the common velocity and pressure conditions (or their derivatives) can be imposed to the boundaries directly, or after simple straightforward discretization. In LBM, however, the boundary conditions described by macroscopic variables have to be appropriately translated into the equivalent conditions in term of mesoscopic quantities and enforced at the mesoscale. In this translation procedure, the mathematical relations among the macroscopic variables (e.g., density and velocities) and the mesoscopic quantities must be satisfied and the known particle distributions need to be respected. Since the number of unknown particle distributions is greater than the number of mathematical macroscopic-mesoscopic relations, additional physical or numerical rules need to be introduced to determine the unknown particle distributions. Examples of such additional rules include momentum preservation, local thermohydrodynamic equilibrium, finite difference extrapolation.

In the theoretical study and practical application of LBM, various lattice models have been proposed and examined: often-used 3D models include D3Q15, D3Q19 and D3Q27, with D3Q19 providing better combination of computational stability and accuracy. Zou & He [Phys. Fluids 9 (1997)] developed a set of analytical velocity and pressure boundary conditions for D2Q9 and D3Q15 LBGK models. However, the analytical boundary conditions of the same kind for the popular D3Q19 model were not provided in their paper, and, to our knowledge, have not been reported elsewhere. In the D3Q19 model examples reported in the literature, the flows are usually driven by body force with solid and periodic boundaries.

In this paper, an analytical boundary condition is derived for D3Q19 LBM, based on the principles of bouncing back non-equilibrium portion of particle distributions in the normal direction and momentum preservation. (This work essentially extends Zou & He's analytical boundary conditions to D3Q19 lattice.) The developed solutions are verified in both steady-state flow and transient flow problems through comparing numerical results with closed-form solutions. The simulations show that the developed analytical boundary condition is accurate for both pressure driven and flux driven fluid flow problems.

ARMA 15-0583

Coupled Waves at Fracture Intersections

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Fracture intersections play a crucial role in the hydraulic connectivity of flow paths in rock, yet no current techniques exist for characterizing the state of an intersection. We demonstrate experimentally and theoretically that elastic waves propagated along fracture intersections are affected by the amount of contact among the blocks forming an intersection.

Conceptually, fracture intersections can be viewed as wedges (corners) coupled through the points of contact along the intersection between fractures. In this study, the boundaries between the different media surrounding the intersection were modeled as a displacement discontinuity, i.e., linear slip boundary condition. Using the solution for a wedge wave and the boundary conditions, an eigenvalue problem was derived to determine the velocity and motion of intersection waves. The resulting wave is a function of frequency, material impedance, and specific stiffness at the intersection.

Group theory was applied to the geometry of the intersection to determine the number and type of modes supported by an intersection. Group theory takes advantage of the symmetries to determine which vibrations are allowed. The symmetry of an intersection made by two orthogonal intersections belongs to the group C_{4v} and results in 6 possible normal vibrational modes, two of which are degenerate. The numerical calculation of the coupled wedge waves at the intersection resulted in four of the five unique normal vibrational modes. Their velocities ranged between the single wedge wave and the bulk shear wave velocity.

Experiments were performed on orthogonal fracture intersections made from four aluminum samples (0.29 x 0.076 x 0.076 m) to detect intersection waves. Biaxial loading conditions were used to change the contact area along the intersection. At low loads the individual wedge waves were excited because the stress between the wedges was not sufficiently high to couple the waves. As the external load was increased, the wedges coupled and propagated at higher velocities, trending towards the bulk shear wave velocity at high applied loads. The specific stiffness of the fracture intersection can be estimated based on the velocity of the intersection wave. Using this estimation the flow path(s) along or through the fracture intersection can be characterized and used as a tool to determine which flow path is most likely for a given sample.

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ARMA 15-0458

DEM Simulation of Brazilian Tensile Failure of Hard Rock in Consideration of Element Configuration

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The Particle Flow Code (PFC), a simulation code based on the distinct element method (DEM), is an effective numerical tool for simulating the failure process of hard rock. By introducing the bonding model (elasto-plastic glue working at particle contacts) and the clump model (a group of rigidly-connected particles to express complex form of real rock minerals), the code has become better able to express the brittle failure of hard rock. However, there is not good way to easily determine appropriate configuration of the clumps. In addition, a problem has arisen, namely, that PFC simulations with the clump often cannot reproduce rapid strain-softening behavior in Brazilian tensile tests. To grasp the effect of clump configuration on the failure characteristics of the model, and to propose a way to determine appropriate clump configuration, this study conducted PFC simulations of Brazilian tensile test and unconfined compression test considering particle and clump size, and compared the results with the experiment. The results show that larger clumps give larger brittleness (the ratio of unconfined compressive strength to Brazilian tensile strength) under the same particle size conditions. The results also show that post-peak stress behavior in Brazilian tensile test is better expressed when smaller size of particle is used, under the same ratio of clump size to particle size. These differences due to clump configuration are related to interlocking effect of neighboring clumps and/or blocking the way of crack propagation by clumps. Based on the simulation results, we discuss the way to determine optimum clump configuration in PFC simulations.

ARMA 15-0456

Development of an exploration, design, and construction system for bedrock reinforcement considering geology at the tunnel

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The primary concern when constructing underground spaces for dumping and storing high-level radioactive waste deeper than 300 m in the earth, and when constructing tunnels for the Linear Chuo Shinkansen 1000 m below earth cover in Japan, is space destabilization due to high ground pressure or sudden water leakage. Therefore, it is necessary to take measures to assure construction safety and maintain the stability of the underground space for as long a time as possible. Furthermore, these structures should be sound and have a quality higher than is required in the construction of ordinary underground structures. Simultaneously, the reduction of construction costs is very important; this means that more efficient and effective designs and construction methods are required.

For this, the authors developed a grouting quality control system (Japanese patent publication number 2013-221298) to provide the best water stopping measures, which differ according to the geological features present, and applied it to the construction of a dam and examined the applicability to underground space construction. To provide the best water stopping measures possible according to the geological features, this system combines the use of (1) a crack density diagram to calculate the direction of the drilled injection holes that will best intersect with extant cracks and (2) a method to draw a contour plot of rock water channels based on the results of geostatistical analyses.

Although the intersection density between grouting injection holes and cracks is important in designing the water stopping measures in anisotropic bedrock, the stability of bedrock around the underground space is also of concern. In other words, for the construction to be efficient and effective, it is necessary that the rock bolts intersect with quite a lot of cracks in anchoring them so as to maintain the stability of the space in bedrock, assuming that the strength is very low in cracks and high in the main body of bedrock.

ARMA 15-0253

Numerical Modeling of Experimental Hydraulic Fracture Initiation and Propagation in Enhanced Geothermal Systems

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The paper presents numerical validation of experimental scale study of hydraulic fracture initiation and propagation for stimulation of Enhanced Geothermal Systems (EGS). The Displacement Discontinuity (DD) Method, which is a variant of the boundary element method (BEM), is used to model the rock matrix deformation and stress distribution around the fracture. Two-dimensional DD model, based on constant strength formulation and parabolic crack tip displacement, is used to account for square root variation of the fracture front fracture toughness and stresses. Effect of fracture height is considered in the formulation. Non-Newtonian fracturing fluid flow is modeled using the standard Galerkin's Finite Element Method. The fracture initiation and propagation process areaddressed following the linear elastic fracture mechanics (LEFM). The hydraulic fracture simulation process presents a complex numerical problem in which physical processes involved such as rock matrix deformation, fracture fluid flow, and fracture propagation are interdependent. The fracture aperture strongly influences the fluid flow behavior inside the fracture, as the fluid velocity is a function of the fracture aperture, and the fluid pressure influences rock deformation process. Hence, these processes of fluid flow, fracture deformation, and propagation are solved in a coupled manner using sequential iterative approach till convergence is achieved. In the scale model study, once fractures connecting the injection and the production well is created, heat circulation test is done. A two-dimensional numerical scheme for validation of the laboratory heat circulation is

developed using boundary integral equation approach. First, details of the mathematical model and methodology are presented. The model is thentested against known analytical solution. Finally, hydraulic fracturing results from a true tri-axial EGS experimental cell developed at Colorado School of Mines were use to validate numerical model results. Parametric studies are done to quantify the effects of different fluid injection rates, fluid injection temperatures, and fluid properties on the fracture geometry. The BEM results in a numerical procedure which eliminates discretization of complete reservoir domain. The paper shows that BEM is a numerically efficient and inexpensive scheme for hydraulic fracture modeling.
Keywords: Enhanced geothermal system, displacement discontinuity method, fracture deformation, hydraulic fracture, non-Newtonian fluid flow

ARMA 15-0007

Stress Evolution of Rock Bolt Elements in Intersecting Joints in Rock Masses

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Computer modeling can be used to explore and gain new insights into the impacts of rock bolt intersecting joints in rock masses, and to estimate the effectiveness of the rock reinforcement system. In order to achieve this goal, numerical simulation was performed using FLAC3D to investigate the stress evolution in the rock bolts. The coupling algorithm is based on the analytically-derived interface behavior between a rock bolt and the rock material for grouted rock bolts. The shear force generated by slippage along the interface is assumed to have a linear relationship with respect to the relative slipping distance between the rock bolt and the rock. The linear elastic criterion is applied to determine the material behavior of rock bolts before the axial stress reaches the yield value. The pullout tests are simulated to verify the coupling algorithm and the effects of the proposed rock bolt elements. The simulation results show that the proposed rock bolt models can predict the shear forces and axial loading along the rock bolts. For the rock bolts observed in this study, the max axial force was within the design limit of the bolts, thus the support design was shown to be acceptable. Finally, parametric study pertaining to length, anchorage length, and rock bolt spacing was carried out with the numerical model, and several suggestions for the support design were proposed, and show that the stress in the rock bolts varied.

ARMA 15-0037

Teaching Subsidence Concepts with a Physical Modeling Device

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A subsidence simulation system using displacement measurement techniques based on opto-electronic displacement measurement sensors has recently been developed. Traditional and optical measurement techniques have been reviewed. Opto-electronic sensors measure distances without contact on granular or even liquid surfaces. A draw-wire displacement sensor is combined to show the position of measurement. This sensor measures the linear movement of a component by means of a wire made of highly-flexible stainless steel strands, which is wound onto a drum by a spring motor.

The cavity making device is a sand box type container with a rectangular opening on the bottom, where a plate that fits the opening is placed. The plate is connected to a micrometer that can move the plate vertically. Five different sizes were used for the opening.

The results of modeling analysis define the parameters of subsidence including angle draws, angle of break, subsidence factors and width/depth ratios of openings with high accuracy in a systematic manner. Subsidence profiles are determined in mathematical forms. The outcomes is useful for interpreting field subsidence data and simulations and teaching the subsidence concepts to

undergraduate class. Results also shows feasibility of obtaining soil shear strength parameters from the subsidence testing as well.

ARMA 15-0090

Prediction of Tunnelling-induced Settlement Using Gene Expression Programming

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The present study aims to apply intelligent method to predict settlement of tunnels. This method can be used for settlement prediction of tunnel future levels. Many parameters affect settlement, but some of them are applicable to empirical equations. Prediction of this phenomenon depends on many parameters and the effect of each parameter on the other ones has made the use of empirical methods impossible. In this regard, the capability of Gene Expression Programming (GEP) method are studied for settlement (S_T) prediction. The intelligent methods have been studied on the basis of data obtained from 50 tunnels all over the world, which have been excavated using the NATM method with similar soil properties. These parameters were collected from previous research data, which the values of settlement were obtained from numerical modeling (FLAC$_{2D}$ software). 30 datasets were applied for modeling and 20 datasets were used for appraising its performance. The values of S_T are predicted by using soil strength parameters (E, C and ø), depth (Z) and diameter (D) of the tunnel. Three equations were also rendered by GEP method. Finally, the results of this method were compared. According to the results, intelligent method are recommended for prediction of the subway settlement.

ARMA 15-0333

Real time stability evaluation of large underground powerhouse caverns - A case study

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Druk Green Power Corporation's (DGPC) IC-1020MW, Tale Hydro Electric Project (THP) large powerhouse caverns are situated in the mighty Himalayan region and close to famous Main Central Thrust (MCT), fault zone. The structures experienced many incidents of strata instabilities during the construction period including large roof falls and they were commissioned in 2005. Since then during the operation these structures they are experiencing violent failure of rock bolts till the date from the side walls of the caverns. Conventional instrumentation that was installed during the construction providing inadequate information to address the problem and it was found there is no scope for the further expansion to densify the same in order to obtain regional strata instability information. During 2009 a high level technical committee felt the need of microseismics and recommended for real time, remote regional microseismic monitoring system after the due trails for its capability, suitability as a solution for the caverns life time regional strata stability evaluation purpose. The objectives of this monitoring is to provide the information related to the caverns regional strata behaviour, strata movant, development of stress pockets, any stress changes in the strata, mainly to study the rock bolt failure problem and to address the structure regional strata stability in condition. A high resolution sixty channel real time, remote monitoring microseismic system is established during September 2013 and being in operation till date without any interruption with noise less data generation. The data is continuously recorded, processed and analysed in near real time at various remote locations after the due calibration and the strata condition information is being provided to the management from time to time. During the one year continuous use of the microseismic monitoring the system recorded microseismic events from rock strata, rock bolt failures including with precursory information in the form of metal failure signatures and microseismic events for few failures, very local (3 to 58 km distance) earth quake signals, which are having high frequencies up to 40 Hz. The microseismic events mapped on the caverns plan in 3D, statistical analysis of events microseismic source parameters was carried out to correlate with the rock bolt failures apart from precursory signals signature study. Non clustering of microcosmic events and major microseismic events so far recorded have the local magnitude of the range only about -2.6

showing the stability of the caverns and the non-development of any stress pockets including the migration (changes in stress) of stress regimes. This paper dealt with the real time microseismic monitoring of regional strata behaviour of underground caverns, correlation of the data to explain the rock bolt failures, strata stability information using results of statistical analysis of microseismic events for their source parameters variations.

ARMA 15-0450

Model test of deformation and failure mechanism of shield tunnel passed through ground fracture with small angle

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Based on the Xi'an metro engineering and the geological environment of Xi'an ground fissure, the physical model test that segment lining structure of shield tunnel passed through ground fissure with 30°was designed according to the similar theory. The strain of segment concrete, longitudinal bolt and circumferential bolt were measured. The contact soil pressure and peripheral soil pressure, convergence displacement of segment lining, the soil settlement on the top of model and other macro-phenomena were measured too. The test results showed that the main deformation and damage of segment lining structure of shield tunnel passed through ground fissure with 30 degree is shearing with distortion on local; the deformation and damage range is from 1.25D(D is the external diameter of segment ring) in the hanging wall to 0.75D in the foot wall; the deformation and damage of segment ring is asymmetric and partial compressive; the dislocation of circumferential seam on the soffit which is up to 40mm(0.033D) is bigger than that of crown and arch waist. It is difficult for segment lining to adapt to 20cm(0.1667D) deformation of ground fissure, and the segment lining structure of shield tunnel is unsuitable to the geological environment with violent activity of ground fissure.

ARMA 15-0511

Development of an oedometer cell to study the horizontal stress evolution during a chemical dissolution

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The recent development of laboratory and field tests techniques, allied to the advancement of computational methods in engineering, has allowed the incorporation of new parameters and equations in numerical simulations, in order to reproduce the behavior of soils and rocks in a restricted way.

Within this context, the main objective of this research was to develop an oedometer cell, in order to measure the horizontal stress and thus, investigate the time evolution of stresses and the strain of synthetic porous medium during the mineral dissolution process throughout the experimental and numerical studies, for the purpose of represent and understand the phenomenon of chemically induced compaction and the impact on your geomechanical and geochemical behavior.

The oedometer cell was developed at the Federal University of Pernambuco-Brazil based on specifications outlined by Castellanza & New (2004). This cell is composed by an aluminum-bronze alloy (height of 65 mm in a 50mm diameter ring and 0.5mm thickness) with data acquisition system specifically designed to measure the vertical displacement and the horizontal stress evolution. The ring with the sample is fixed by top and bottom caps. The upper and bottom caps have inlet and outlet water connections. The vertical displacements and horizontal stress are measured by LVDT and strain gauges, respectively.

To achieve these objectives, the tests were performed in the synthetic porous medium (mixtures of glass beads and NaCl) using the oedometer cell developed in this research. The experimental tests were separated into three steps: (1) determination of the yield stress of the synthetic porous medium,

(2) assessment of the samples behavior after the partial dissolution process, and (3) determination of the horizontal stress and the sample strain during chemical dissolution.

Regarding the experimental results, in the first step of tests the yield stress of 20kPa was obtained for samples tested without chemical dissolution. The tests carried out with total minerals dissolution showed that the horizontal stress decreased in the beginning of the process and then, a gradually increase was observed, reaching volumetric strain values up to 18%.

Concerning the numerical simulation, the experimental data were used in the model implemented by Silva (2012), employing the BBM (Barcelona Basic Model) and the model developed by Castellanza and Nova (2004) to describe the plastic strain due to the chemical effect. During the NaCl dissolution, the numerical simulation was able to represent the sharp decline of the volumetric strain of the synthetic porous medium, as well as, the model was able to reproduce the changes of the effective horizontal stress observed in the experimental data. Thus, a good agreement between the experimental and numerical data was reached.

ARMA 15-0598

Experimental and Numerical Investitaions on Mixed Mode Fracturing of Concrete and Rocks by using Semi-Circular Disc (SCD) and Disc Specimens

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Abstract: Sudden and violent fracturing of brittle materials, such as natural-forming rocks and artificial aggregates like concretes, still remain one of the leading causes of fatalities in mining, civil and geotechnical industries today. The primary aim of this research work is to investigate the mixed modes I (tensile) and II (shearing) fracturing mechanisms of Brisbane Tuff rock and laboratory-prepared concrete samples using Semi-Circular Disc (SCD) and Cracked Chevron-Notched Brazilian Disk (CCNBD) specimen geometries (Fig.1). The experiments mainly involved subjecting the CCNBD samples to diametral compressive loading and the SCB samples to three-point bending. In order to create various mixed mode loading conditions, the chevron notch cracks of the CCNBD specimens were oriented at notch crack inclination angles, β, of 0°, 30°, 45°, and 70° as part of the diametral testing procedure, whilst the SCB specimens were cut at the same βs prior to conducting the three-point bending tests. The experimental study revealed that the CCNBD geometry and the Brisbane Tuff rock have higher failure loads than the SCD geometry and concrete sample counterparts. Further observations show that unlike the SCD specimens which only generated primary cracks, the CCNBD specimens generated two types of cracks, namely wing cracks and secondary cracks. Subsequent to the experimental investigations, the theoretical analyses were then done to calculate the Modes I and II fracture toughness values of the samples. Based on the theoretical results, the SCD geometry yielded anomalous values for Mode I stress intensity factor, KIc, for both rock and concrete samples. Following the experiments, a series of numerical analyses were then performed using a Finite Element Method (FEM) software known as FRANC2D to simulate the stress distributions and fracturing behaviour of the samples at different β, as well as to obtain the Modes I and II stress intensity factors (Fig.2). According to the numerical results, it was unlikely to obtain pure Modes I and II using both the CCNBD specimens under diametral compressive loading, and SCB specimens under three-point bending. Overall, this investigation evident that β, and hence the mixed mode loading condition, is a function of failure load, stress distributions, position of the pre-existing cracks relative to the major principal stress and fracturing behaviour of brittle materials.

ARMA 15-0643

Investigation of Repetitive Damage Sections about the Roadside Debris Flow and Evaluation of Efficiency of Installing Facilities for reducing Debris Flow

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South Korea is composed of mountains more than 70% of the Country. Occurrence of slope was inevitable through constructing road, there are lots of slope without stability that built with rapid economic growth in the past. Thus, the large and small rockfall or landslide have been constantly occurring during the summer torrential rains that is being generated than 60% about the annual precipitation. But for recent 17 years, the collapse of artificial slope about casualties and property damages are being decreased compared to the past by providing nationwide investigation and preparatory measures at the national level to roadside artificial slope.

Meanwhile, debris flow that is like water with debris accumulation such as soil, rock and arbor in a natural mountain was not interested compared with the artificial slope. After quite a number of casualties and property damage caused by occurring a large debris flow around Namyangju(2009), Woomyun-Mountain(2011) and Central Expressway Chunchon IC(2013), social interest and its precautions about debris flow are required to prepare.

The purpose of this research is to promote disaster prevention about unknown debris flow by establishing census and precautions of repetitive damage sections rather than post-investigation and countermeasures about debris flow disaster area simply. Firstly, to set specific trial section then finding the way about debris flow damage prevention method, currently corresponds situation and investigation.

The selected field investigation section that Route 6(bongpyeong – Hoengseong) and Route 56(Chuncheon- gyeongpo) are concerning debris flow damage at roadside on mountain is about 50km.

The debris flow checklist was created for collecting objective data from various investigators including valley location, topography and geometric information, hydrology and geology, geotechnical information, facility information.

The distributed rock facies along the Route 6 is biotite granite and biotite granodiorite, the direction of valley has developed mostly north-south, northwest-southeast to east-west. As the average slope of valley is 31°, slope range of valley which observed occurrence history of debris flow has widely shown 20° ~ 44°.

Rock facies along the Route 56 is gneiss complexes including banded biotite gneiss, granite gneiss and pyrrhotite gneiss, etc., it has feature developing that foliation has a gap around 5cm approximately. The valley along the Route 56 is mostly developing northeast-southwest direction, it shows 32° average slope, direction and angle of inclination of the valley seems almost parallel orientation of the foliation.

50 sites in Route 6 were investigated through field investigation, facilities for reducing debris flow damage in 19 sites did not build. Furthermore, 86 sites in Route 56 were investigated, facilities for reducing debris flow damage in 70 sites did not construct and there are multiple site that need to prepare urgent precautions in case of debris flow.

In this research, numerical analysis on the effects of damage reduction facilities such as check dam conducted to expected sites of debris flow using distinct element method “PFC2D”. Assumed that slope collapse occur at 80m of height of the valley based on terrain information through field investigation, gradient of the valley gave change as 30°, 25°, 20° from the lower parts of the valley, distance of debris flow occurrence set 100m. Control facilities of bottom of the valley were assumed that height of concrete check dam was 3m, case 1 that installed check dam at bottom of slope to secure capture distance 5m and case 2 that built additional check dam at height of 15m were divided, debris of 200 was produced to apply that diameter of each individual debris is 0.2~0.8m in the same.

At results of numerical analysis, the force of case 2 exerted the half of the force (890kN) of case 1 was 410~450kN at designed check dam, overtopping(2%) of case 2 have been found to be expected to decrease about 1/15 than overtopping(31%) of case 1.

Therefore, when to design check dam considering force exerted by debris flow and overtopping, installing several check dam of small size in the valley was determined to be more effective than installing solitary check dam of large size in lower of the valley for reducing damage of debris flow.

ARMA 15-0668

Influence of Structuration on the Critical State Friction Angle: an Elastoplastic Description

Morteza Mohamadi[1]
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Many natural clays/clay-shales manifest evidence of structuration in their mechanical behavior. The two widely accepted features of structuration in the behavior of natural clays are: 1) existence of a yield stress being larger than the preconsolidation stress and 2) stiffer behavior with higher strength in spite of larger liquidity index than reconstituted soils. Numerous constitutive models in the context of unconventional plasticity have been proposed to account for these changes by introducing softening of a structure-related yield surface with a measure of plastic strain, e.g. Asaoka et al (2000), Rouainia and Muir Wood (2000), Nakai et al (2011). However, more recently Taiebat et at (2010) proposed an evolution rule to account for the influence of structure degradation on the critical state friction angle.
In the present study a simplified version of the model proposed by Nakai et al (2011), is extended to incorporate evolution of the critical state friction angle with destructuration. A new evolution rule is proposed by introducing one material parameter controlling the pace with which friction angle degradation occurs. A non-associative flow rule is invoked by simply turning off the new internal parameter in the yield surface to obtain the plastic potential. Model simulations of lab experimental tests on Colorado shales are presented in order to depict how the proposed modification adds more flexibility to the original model. Finally, results of some previously published experimental studies on natural clays/shales and cemented sands are gathered to verify existence of structure-dependent critical state line, particularly in the meridian plane, and to examine the efficiency of the proposed modification.
Key words: Elastoplastic, Natural clay, Structuration, Critical state friction angle.

ARMA 15-0688

Case Study on Field Investigation and Stability Analysis of Volcanic Rock Slopes in Southwest area of Korea

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Volcanic activity often makes very complicated volcanic complex due to an admixture of lava flow and sedimentation of volcanic ash. Song-Gok site is composed of volcanic rocks and collapsed at the lower part of the slope as a combination of several discontinuities in and around a fault. The result of projection analysis indicated the possibility of plane, wedge, and toppling failure in the failure section. The result of discontinuities modelling using Distinct Element Method(DEM) showed that total displacement is 207mm, joint shear displacement is 114mm. And yield surface zone was verified at the fault plane of the failure section. Volcanic rock's slopes is vulnerable in geotechnical characteristics, which is caused by differential weathering among rocks, effect of groundwater based on permeability of rocks, and systematic joints generated by cooling and contraction of lava. When considering stability of volcanic rock's slope, data such as geological features of the rock through detailed geological survey and variations of discontinuities and rock blocks should be utilized.

MIN-P-02:

Tuesday, June 30, 2015, 03:30 pm - 04:30 pm

ARMA 15-0161

A Parametric Study of Critical Factors That Affect Stability of a Cavity Induced by Borehole Mining in a Coal Deposit

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A Parametric Study of Critical Factors That Affect Stability of a Cavity Induced by Borehole Mining in a Coal Deposit

A sensitivity analysis comparing the influence of different factors on predicted induced principal stress around the cavity roof was performed. A finite difference method (Flac2D) was applied to study a cavity under internal pressure. The cavity was previously introduced by in-situ borehole mining. The roles of the parameters along with their uncertainties were applied in the measuring of the sensitivity. The sensitivity of internal pressure, cavity geometry, horizontal stress, depth of cover and rock mechanical properties (i.e. cohesion, density, friction angle, Young Module, Poisson ratio and tensile strength) was studied. Largest principal stress is considered as one of the key factors to initiate fractures in the rock. The maximum normal stress criterion also known as Coulomb's criterion is based on the Maximum normal stress theory. According to this theory failure occurs when the maximum principal stress reaches the ultimate strength of the material for simple tension. Based on this theory, the largest principal stress will initiate cracks in the rock and lead to the failure of rock mass. The results showed that the induced principal stress is less sensitive to Young modulus and Poisson ratio. The results show the high impact of internal pressure, cavity geometry, and horizontal stress, depth of cover, friction angle, and cohesion and dilation angle. According to the results of sensitivity analysis, the principal stress is not influence by tensile strength of the rock mass formation.

ARMA 15-0577

Coupled interactions between coal fracture containing gas and the induced shock monitored by microseismic and acoustic emissions

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[1]China University of Mining and Technology

Abstract: Rockburst and gas outburst are two typical coal-rock dynamic disasters closely associated with mining activity of gas-containing coal seam in deep mines. They are characterized by intensive damage and extremely complex triggering mechanism. Furthermore, the prediction is still a mystery, even after a long history of research. Thus, clear understanding of coupled interaction effects between coal-rock and the accumulated gas subjected to static and dynamic loading, such as coal-rock fracture, gas desorption and gushes and induced microseismicity (MS), will be crucial to convince the public that coal-gas dynamic disasters can be effectively monitored and warned. Here, we attempt to fill this gap by gathering the MS information available on the interactions of gas with coals and the effects of coal-rock fracture on methane emission in order to improve the predictability. The presented investigation theoretically explained two following phenomena on the interaction effect of coal fracture and gas emission. 1) The overpressuring gas in the coal immediately can induce crack initiation and growth, which can potentially create a highly permeable damage zone. This type of coal fracture, which is even called gas outburst rockburst, is triggered by the coupling between the unloading of the porous material and the gas storage structures and the expansion due to shock desorption of methane gases induced by energy input of dynamic stress wave. 2) According to coal mass subjected to high static stress and dynamic loading, within the region of the shock wave there may occur the destruction of the coal-and-gas medium, as well as phase transition of gas deposited there. Due to smaller pressure and desorption energy of gas, only abnormal gas emission is formed through the formed fractures and cracks in coal mass.

Accompanied with above-mentioned two process occurrence, MS and acoustic emission (AE) produced by rapid microcrack growth is a ubiquitous phenomenon associated with coal-rock fracture and has provided a wealth of information regarding the failure process in coal-rock. By using MS&AE monitoring systems, two unusual gas emissions occurred in a gas-contained seam of Junde coal mine were recorded in detail. Based on the analysis of MS&AE activity and energy variation prior to, during, and after gas emissions, especially the frequency-spectrum evolution rules manifested medium fracturing strength and type, the corresponding mechanism of two gas emissions were clearly revealed. Simultaneously, it is verified that there is a good correlation between rockburst danger and high methane gas emission events at the mine site. Therefore, MS&AE measurement is an important tool for monitoring rockburst and gas emission, and such monitoring is necessary for maintaining maximum long-term safety.

Key words: coal-and-gas medium; coupled interaction effects; shock desorption; MS&AE monitoring; frequency-spectrum evolution

ARMA 15-0649

GEOMECHANICAL BACK ANALYSIS OF MEASURED OVERBREAK AT THE CRUSHER CHAMBER OF DACITA PROJECT, EL TENIENTE MINE

Alejandro Espinosa[1], Pedro Landeros[1]

[1]*CODELCO*

During development and construction stage of the crusher chamber of Dacita Project at El Teniente mine, instabilities such as rock fall due to the looseness of rock mass confinement took place mainly in zones with singular geometries, related to interfaces between excavations with different sizes.

In this sense, with the purpose of evaluating deviations that the design implementation could have, geomechanics monitoring plan considered several topographical tri-dimensional measurements with a laser scanner, using LiDAR technology. These measurements allowed obtaining the as-built geometry with a millimetric precision, generating point clouds, which were later processed in order to analyze statistically differences in time, in other words, to monitor deformation fields in large scale.

This information corresponds to the base line to future measurements, which will allow quantifying potential changes that the chamber could have in terms of geometry. Besides, it represented an opportunity to develop local calibrations for the tri-dimensional numerical models, built in the design stage. One of the parameters used to evaluate the stability of the design was the minor principal stress, which is directly associated to the rock mass confinement around an excavation.
The tri-dimensional numerical model built on the feasibility stage was used to calculate the stress tensor on each point of the cloud obtained by LiDAR. Then, results were filtered, considering all the points with lower scatter. The first filter was related to the orientation of the principal stresses, discarding points outside the preferential azimuth and plunge for each component. By the other hand, the second one was related with the magnitude of the mean stress. A frequency histogram was used and it was possible to identify two populations of data, depending on the depth of the overbreak compared to the geometry of the design.

Finally, results obtained from the back-analysis allowed to corroborate initial design considerations and to consolidate necessary background information for the evaluation of potential additional excavations, near the main chamber, that could be required for further operational conditions.

ARMA 15-0676

Optimizing the Performance of ANFIS using the genetic algorithm to estimate the deformation modulus of rock mass

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Among the rock mass properties, deformation modulus of rock mass (E_m) is important for implementation and successful execution of rock engineering projects. The direct field measurements of modulus determination is costive and sometimes difficult to execute; however indirect estimation of the modulus using regression based statistical methods, artificial neural networks (ANN) and fuzzy logic (FL) systems are recently employed. Despite the extensive application of ANN and FL in rock mass properties estimation, they are also associated with some disadvantages. In order to improve FL performance, it is possible to incorporate it to ANN. Therefore, adaptive neuro-fuzzy system (ANFIS) was presented. In this system, ANN is used to learn fuzzy rules. However, some parameters of ANN which are left should be optimized. As ANN is structured within the ANFIS, finding the optimum architecture of ANFIS will be very time-consuming via a trial-and-error approach. This study focuses on the efficiency of the genetic algorithm (GA) to find the optimum ANFIS structure and its application to predict the deformation modulus of rock mass. GA is utilized to find the optimal number of membership function, the learning rates and the momentum coefficients and to select the input variables. The results are then compared with those of trial-and-error procedure. A database including 188 data set from six dam sites in Zagros Mountains in Iran was employed using the purpose method. It has been shown that the hybrid ANFIS-GA model has higher accuracy than the trial and error model for estimation of E_m.

Keywords: Deformation modulus, Rock mass, Neuro- Fuzzy system, Adaptive Neuro Fuzzy Inference System (ANFIS), Genetic algorithm(GA).

ARMA 15-0198

A Method for Simulation of Longwall Goaf

Gautam Banerjee[1], Nilabjendu Ghosh[1], Dilip Kumbhakar[1], Keshar Yadava[1]
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This paper describes a method for simulating the goaf of mechanized longwall panels at shallow depth in various coal mines in India for prediction of subsidence, abutment pressure and stresses over goaf and barrier pillars.

As the longwall face advances, the overlying strata caves in and the goaf so formed gets filled up with fragmented rock material that provides resistance to the lowering of the relatively intact strata. The amount of resistance offered by the goaf depends on its compaction and caving behaviour of the overlying roof rocks. Proper modelling of goaf is necessary for the accurate prediction of stress distribution around the face and subsidence at the surface. In this paper, the broken rock debris has been modelled as a non-linear stress strain characteristic to simulate Salamon's [1] theoretical non-linear fill material model. Two characteristic property namely b_g, corresponding to the maximum asymptotic strain (maximum goaf strain) and a_g, representing the vertical stress developed in the goaf at half of this maximum strain, have been identified which describe the stress-strain behaviour.

This study was undertaken to find out the goaf properties for seven previously worked longwall panels at shallow depth. The panels have been chosen based on differences in cavability of roof rock layers and has been classified as easily cavable, moderately cavable and difficult to cave roof. A numerical model is developed in FLAC3D, a finite difference modelling tool and the modelling procedure has been described. Three parameters viz. maximum surface subsidence over the panel, average load on barrier pillars and vertical stress distribution over the stabilized goaf were observed. The results obtained from modelling were compared with field observations in case of subsidence and theoretical values in case of stress distribution over the stabilized goaf and average load on

barrier pillars. This paper provides the characteristic values for the goaf properties for the three different roof-rock type which may be used for simulating the goaf.

ARMA 15-0308

Investigation of rock fragmentation mechanism using dynamic spherical crushing test

Sheng Huang[1], Kaiwen Xia[1], Bibhu Mohanty[1]
[1]University of Toronto

Rock crushing is an integral part of mining industry. It is used either for breaking rocks to extract specific minerals or for obtaining rock fragments to satisfy the requirements of construction industry. However, rock crushing mechanism is still not well understood. During crushing, rock is subjected to dynamic loading and the particle shape influences the fragmentation of crushed rock. Thus, the dynamic ball compression test was performed to improve the understanding of the elementary crushing mechanism.

In this work, a Kolsky bar system and high speed cameras were utilized to carry out a single ball crushing test, with the objective to establish a quantitative relation between input energy and rock particle fragmentation. Ball samples of rock were adopted to avoid the shape effect on fragmentation process. The moment-trap technique was utilized to prevent multi-pulse loadings on the rock sample. The energy absorbed by samples was accurately determined from the one-dimensional wave analysis and the kinetic energy of the sample fragments was estimated from the high speed camera snapshots. The crushed samples were recycled after the test. In addition, by counting the newly generated surface from sample fragments, the surface energy was determined for each sample. The ball compression strength was calculated based on the elastic mechanics theory. The fragment velocity is in the range from 9.2 m/s to 20 m/s, which is linear with the square root of the loading energy. The ratio between kinetic energy and energy absorbed by the sample generally decreases from 80% to 40%, with the increasing loading energy. The determined surface energy increases with the loading rate. The above results necessitate a trade-off between the fragment size and energy consumption.

Technical Session 29 – California West
Hydraulic Fracture Complex Fracture Growth

Tuesday, June 30, 2015, 04:30 pm - 06:00 pm

Chairs: Ghazal Izadi & Daniel Moos

ARMA 15-0671

Numerical Investigation of a Hydraulic Fracture Bypassing a Natural Fracture in 3D

Pengcheng Fu[1], Leonardo Cruz[2], Daniel Moos[2], Randolph Settgast[1], Frederick Ryerson[1]
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In rock formations exist various kinds of obstacles that prevent a hydraulic fracture from propagating along the ideal flat plane dictated by the orientation of the minimum principal in situ stress. An example is an oblique natural fracture being intersected by the trajectory of the hydraulic fracture. In a 2D space, the natural fracture under certain conditions, such as high oblique angle, low differential stress, and low interface friction, would “arrest” the hydraulic fracture and divert the fluid from the latter, thereby preventing it from further growing. However, a hydraulic fracture (assuming to be vertical) in 3D can continue to propagate over and below the vertical extent of the natural fracture and cut the natural fracture from the back wall. This indirect “crossing” mechanism through hydraulic fractures “by-passing” natural fractures has recently been demonstrated by laboratory experiments (Bahorich, Olson, and Holder, 2012) and has important implications for understanding the role of natural fractures in hydraulic fracturing.

We study the pressure signature of the by-passing process by simulating it in a full coupled 3D hydraulic fracturing model called GEOS. The efficacy of the model in simulating hydraulic fracturing is verified against the classical PKN model, and that in simulating the by-passing mechanism is validated against the experiment by Bahorich et al. (2012). The full 3D model enables including natural fractures of arbitrary locations, dimensions, and inherent mechanical and hydrological properties. The pressure required to inject fluid at a given flow rate naturally emerges in the simulation results. The results of the current study offer practically useful guidelines for pressure diagnosis that infers hydraulic fracture propagating processes.

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ARMA 15-0080

Coupling Fluid Flow and Geomechanics in a Three-Dimensional Discrete Fracture Network Simulator

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[1]the University Of Texas At Austin

In the past few years, there has been rapid growth in production from unconventional oil and gas resources using hydraulic fracturing. Hydraulic fracturing in shale is very different than in conventional reservoirs. The classical concept of hydraulic fracturing is that a single planar fracture initiates and propagates through the formation. But it is now understood that in shale, fracturing often forms a complex fracture network.
CFRAC is a discrete fracture network simulator that fully couples fluid flow with the stresses induced by fracture deformation in large, complex networks. Fracture elements are allowed to slide or open and the stresses induced by the fracture are calculated using the boundary element method (BEM). Until the present, CFRAC has been two-dimensional, treating individual fractures like lines rather than planes. Calculations of stresses induced by deformation can be partially adjusted to account for the finite height of the formation, but these techniques are imperfect.
To overcome the simplifying conditions of planar fracture, we have developed a novel, three-dimensional method for modeling hydraulic fractures caused by injection. The model uses the Okada boundary element method to calculate stresses induced by deformation on a rectangular plane. The fractures are discretized in both the vertical and horizontal direction, and fractures can propagate either vertically or horizontally. This entirely three-dimensional simulator also considers the fracture containment due to different stress layer zones: however, the only limitation is that the fracture elements must be rectangular and the fractures have to be vertical.
We performed the following simulations: (1) opening of a circular crack at constant pressure (with comparison to analytical solution), (2) sliding of a circular crack under a uniform far field shear stress (with comparison to analytical solution) (3) propagation of a single hydraulic fracture (with comparison to the PKN analytical solution), and (4) sliding of multiple, interacting strike slip faults in response to fluid injection which shows a path-dependency of the problem. A mesh refinement study was also performed in order to identify the degree of discretization refinement that is necessary to ensure accurate results.
The newly developed algorithm demonstrates exceptional computational efficiency and is fully convergent to classical fracture mechanics solutions. The simulation techniques push the state of the art and have many applications to modeling of hydraulic stimulation, structural geology, and other disciplines.

Keywords: Hydraulic Fracturing, Unconventional resources, Boundary Element Method, 3D complex fracture network

ARMA 15-0132

An experimental study on interaction between hydraulic fractures and partially-cemented natural fractures

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The interaction between hydraulic fractures and pre-existing natural fractures can strongly influence the fracture network geometries and are widely recognized as one of the main issues for understanding hydraulic fracture propagation in unconventional reservoirs. Most experimental studies on this phenomenon treat natural fractures as frictional continuous interfaces with no cohesion (T.L. Blanton, 1982; C.E. Renshaw and D.D. Pollard, 1995) or very weak cohesion (H. Gu et al., 2011). However, it is almost a ubiquitous feature that natural fractures (joints, faults, and veins) in real reservoirs tend to be partially or fully filled with mineralization. For shale reservoirs this cement is often calcite while in sandstone reservoirs it is common to encounter quartz-filled veins. From a mechanical perspective this ought to be an important distinction that should lead to differences in hydraulic fracture growth and hence the stimulation approaches that will be successful.

This paper will present experiments designed to investigate interaction between hydraulic fractures and natural fractures that are strongly cemented but over only a portion of the area of the natural fracture. We find that the hydraulic fracture penetrates directly through a fully and strongly cemented. The contrasting case is formation of a fully offset crack path due to the interactions with an uncemented interface under low stress conditions. We then vary the proportion of the natural fracture that is strongly cemented. In these partially-bonded cases, and most notably in cases of oblique intersection, the hydraulic fracture is observed to persist through the entire height of the specimen both before and after the pre-existing interface. However, the fracture path persists directly through the strongly bonded portions while there is an offset at the unbonded portion. These initial results in this novel but almost certainly realistic configuration of partial bonding suggest that a relatively small bonded region(s) can be sufficient to promote crossing with the hydraulic fracture apparently growing both in length and height after crossing.

ARMA 15-0119

Fully 3D Hydraulic Fracturing Model: Optimizing Sequence Fracture Stimulation in Horizontal Wells

Ghazal Izadi[1], Michael Gaither[1], Pengcheng Fu[2], Leonardo Cruz[1], Daniel Moos[1], Christine Baba[1]

[1]Baker Hughes, [2]Lawrence Livermore National Laboratory

Hydraulic fracturing is a reservoir stimulation technique which in unconventional (e.g. shale gas or oil) plays is required to generate sufficient reservoir contact to enhance production. Frac design approaches use fracture spacing, sequence, and other parameters to enhance fracture complexity through modification of the local stresses within the stimulated area. Conventional frac designs consist of a series of stages within a well stimulated sequentially, from toe to heel. A newer promising design is a zipper frac, where two parallel horizontal wells are stimulated stage by stage alternating between wells in a "zipper" pattern; the effectiveness of zipper fracs has been demonstrated by industry, however the treatment optimization is still under development.

In this paper a fully 3-D (non-planar) reservoir model is used to capture some of the fundamental effects which influence fracture growth and complexity during stimulation using the zipper frac approach. We evaluate quantitatively the effects of controllable parameters such as stage spacing, well spacing, injection fluid type and rate and net pressure for different well and completion configurations. Three designs are investigated: conventional, zipper frac, and modified zipper frac. In the modified zipper frac the stages are placed in a zipper pattern, but the first and second interval from the first well are stimulated one after the other, then the intervening interval between these first two intervals is stimulated in the second well, and stimulation continues alternating between the first and second wells. The results demonstrate quantitatively the changes in the stress state, the resulting degree of activated fracture network complexity, and the geometry of the propped fracture, caused by variations in operational parameters. The stimulation model is also used to predict early-stage flow-back and production. Results demonstrate that the zipper frac approach improves performance due both to optimizing the distribution of fracture aperture and by increasing reservoir contact area, and those significant differences in fracture geometry result from modifying the order in which adjacent wells are stimulated.

ARMA 15-0299

3D simulation of fluid-pressure-induced fracture nucleation and growth in rock samples

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In recent years, hydraulic fracturing has been widely used to stimulate a reservoir volume in low permeability formations. By injecting fluids and/or chemicals into a wellbore, a pressure pulse sufficient to induce fracturing is generated. The newly-formed fracture network increases the hydraulic conductivity close to the wellbore, thus increasing hydrocarbon extraction rates. However, reproducing the resultant complex fracture growth in numerical models remains a challenging research topic.

In this study, a three-dimensional (3D) hybrid Finite-Discrete Element Method (FDEM) is used to investigate the complex fracturing behavior around a stimulated wellbore. FDEM is an explicit numerical method which combines continuum mechanics principles with discrete element algorithms to simulate multiple interacting deformable fracturable solids. Using FDEM, the stimulation process is modeled in an unconfined 10in x 10in x 10in cube of Indiana limestone with an internal cavity of 1.5in (diameter) x 3in (height), 2in below the cube surface. The pressure pulse is applied on the perimeter of this cavity. The simulation results are verified against laboratory experiments (Al-Nakhli et al, 2014)

The simulation results shed light into the complex fracture growth regime around the cavity. As the pressure pulse is applied, fracturing initiates in Mode I (tensile) on top of the cavity (Figure 1). At later stages, Mode II (shear) fractures also develop alongside Mode I fractures and on the periphery of the cavity. This fracturing mechanism continues for as long as the pressure is applied until full rupture of the block.

Three different pressure pulse profiles are studied. The extent and mode of damage is shown to vary based on the applied pressure pulse. Also, a parametric study on the influence of strength properties on the failure mechanism of the block is performed. Finally, the effect of adding external confining pressure on the fracture growth and breakdown pressures are studied.

Overall, the simulation results illustrate good agreement with experimental findings including fracture patterns and breakdown pressures. As a result, suitability of 3D FDEM to model the complex rock fracture initiation and growth is illustrated.

ARMA 15-0249

3D modeling of hydraulic fracturing and stress perturbations during fluid injection

Vincent Roche[1], Mirko van der Baan[1], Giona Preisig[2]

[1]University of Alberta, [2]University of British Columbia

The models are performed using a hydromechanic discrete-element method. The hydraulic fractures are simulated during fluid injection in a homogeneous rock that has the mechanical properties of granite. Several configurations of pre-existing fracture sets are investigated. A test model is used to simulate the development of a planar hydraulic fracture in a non-fractured rock (Figure 1A). In a second set of models, a planar hydraulic fracture grows within a rock affected by pre-existing joint sets that are connected to the fluid injection (Figure 1B). In a third set of models the pre-existing joint sets are disconnected from the fluid injection.

For the different models, when injection starts, the pore pressure increases then reaches a threshold that coincides with the fracture propagation. At this point, the pore pressure slightly oscillates due to failure of elements and is approximately equal to the least principal stress plus the fracture strength.
For the test model, the hydraulic fracture growth follows the horizontal plane with a mostly circular front. The maximum aperture is linearly linked to the length of the fracture. The proportionality constant and the penetration rate are consistent with the development of an opening fracture in impermeable purely elastic rock. The stress field is mainly modified in two distinct areas. Near the fracture tips, the stresses decrease indifferently to the hydraulic fracture growth. Conversely, the stresses increase and the fracture propagation promotes stress perturbation in the fracture walls.
For the model with pre-existing fracture sets that are connected to the fluid injection, the fluid flows into the best oriented pre-existing fracture rather than forming a new hydraulic fracture. The penetration rate is more important and the pore pressure inside the reactivated pre-existing fracture is lower than in the test model. Finally, the increase in stress, due to opening, is significantly reduced in the fracture walls.
For the model with pre-existing fracture sets disconnected to the fluid injection, the penetration rate and as the pore pressure are similar to the test model. But the elastic stress perturbation is reduced in the fracture walls.
Our results show that interaction of a hydraulic fracture with pre-existing fractures can be complex. Pre-existing fractures connected to the hydraulic fracture increase the volume stimulated directly by the fluid injection. However, pre-existing fractures also affect the stress field pattern around the injection. This may inhibit local elastic fracture triggering and significantly affect the leak off into the rock matrix.
Acknowledgments

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Technical Session 30 – California East
New Developments in Computational Rock Mechanics
Tuesday, June 30, 2015, 04:30 pm - 06:00 pm
Chair: Scott Johnson

ARMA 15-0568

APPLICATION OF HPC AND NON-LINEAR HYDROCODES TO UNCERTAINTY QUANTIFICATION IN SUBSURFACE EXPLOSION SOURCE PHYSICS

Souheil Ezzedine[1], Oleg Vorobiev[1], Lewis Glenn[1], Tarabay Antoun[1]
[1]*LLNL*

To understand the genesis of shear wave generation observed during monitoring underground explosions several real-life tests (Source Physics Experiments, SPE) in fractured granitic rock mass were conducted at the Nevada National Security Site (NNSS). Fractured rock masses present several challenges: 1) fractures are poorly characterized and sparsely sampled in space, 2) the geomechanical and geophysical properties of fractures are not well known and their measurements are only made at the laboratory scale, and 3) the spatio-temporal scale disparity between the near source explosion physics and the far field elastic wave propagation physics requires considerable computing resources to simulate geophysical signatures from end-to-end source-to-receiver. In order to build a credible conceptual model of the subsurface we integrated the geological, geomechanical and geophysical characterizations conducted at the NNSS. Because detailed site characterization is limited, expensive and, in some instances, impossible we have numerically investigated the effects of the characterization gaps on the overall response of the system. Using HPC resources at LLNL, we performed several computational studies to identify the key important geologic features – joints (hundreds of thousands), faults, saturated versus dry layers, topography etc. -- that affect the most the ground motion in the near-field and in the far-field using stochastic representation of the complex subsurface. By using brute force Monte Carlo simulations and by sampling judiciously the large hyperspace of parameters we have probabilistically conducted several sensitivities studies on the geological, geomechanical and geophysical parameters. Such studies would help guiding site characterization efforts to provide the essential data to the modeling community. We validate our computational results by comparing the SPE measured and computed ground motion at various ranges and we show that the discrete nature of rock masses is important to understand ground motions induced by underground explosions and that the fractures are the main cause of shear motion generation.

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ARMA 15-0487

Numerical simulation of crack initiation and growth in rock specimens containing a flaw under uniaxial compression

Ahmadreza Hedayat[1], Felipe Ochoa-Cornejo[2], Yazen Khasawneh[3]
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The understanding of failure process of brittle rock is critical for a number of geomechanical applications including hydraulic fracturing for the stimulation of hydrocarbon reservoirs and the associated induced seismicity, wellbore stability in drilling, geothermal reservoirs, and CO_2 sequestration. Extensive experimental studies have been performed to understand the fracturing process in brittle rocks under uniaxial compression and several types of cracks including tensile, shear, and combined tensile-shear have been observed at the tip of pre-existing flaws. In this study, numerical simulations of a single oriented flaw in brittle rock materials in uniaxial compression were carried out using the extended finite element method (XFEM) and the boundary element method (BEM). The Abaqus commercial package was used for the XFEM simulations, whereas the displacement discontinuity code FROCK was used for BEM simulations.

The code FROCK uses a stress-based criteria to model crack initiation and growth. In this criterion, the crack initiation depends on the local stress relative to the strength of the material rather than the Stress Intensity Factor (SIF). Since the stresses at the tip of the crack are much higher than the strength of the material, a plastic zone with a certain radius, as a material property, is assumed to form at the tip of the crack. A tensile crack initiates when the tangential tensile stress at the plastic radius reaches the critical tensile strength of the material and similarly a shear crack initiates when the shear stress reaches the critical shear strength of the material. In XFEM analysis, the maximum principal stress (MAXPS) failure criterion was selected for damage initiation. This criteria assumes that the crack propagates in the direction perpendicular to the maximum principal stress. The numerical simulations were in good agreement with the experimental results in predicting the tensile (wing) cracks. Figure 1 shows the XFEM results indicating the crack initiation and propagation in a rock specimen containing a 45° single flaw in uniaxial compression. The SIFs obtained from FROCK and XFEM were close to the values obtained from the closed-form solutions available for mixed-mode loading. However, the numerical simulations only presented the tensile cracks and failed to predict the shear cracks.

ARMA 15-0311

Anisotropic geomaterial deformation formulation for the combined finite-discrete element method in 2D

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In this paper, the combined finite-discrete element method (FDEM) has been applied to analyze the deformation of anisotropic solids, in particular anisotropic geomaterials. In the most general case, in the context of FDEM, geomaterials are both non-homogeneous and non-isotropic. With the aim of addressing anisotropic material problems improved 2D FDEM formulations have been developed. These formulations feature the unified hypo-hyper elastic approach combined with a multiplicative decomposition based selective integration for volumetric and shear deformation modes. This approach is significantly different from the co-rotational formulations typically encountered in finite element codes. Unlike the co-rotational formulation, the multiplicative decomposition based formulation naturally decomposes deformation into translation, rotation, plastic stretches, elastic stretches, volumetric stretches, shear stretches, etc. In essence, all these deformation modes are obtained from the displacements being described by a composition of the respective functions; which, when derivation is applied, results in multiplication, thus the name multiplicative decomposition. This type of decomposition can be implemented for a whole family of finite elements from solids to shells and membranes.
This novel 2D FDEM based material formulation was designed in such a way that the anisotropic properties of the solid can be specified in a cell by cell basis, therefore enabling the user to seed these anisotropic properties following any type of spatial variation, for example following a curvilinear path.
Due to the selective integration, there are no problems with volumetric or shear locking with any type of finite element employed. In addition, multiplicative decomposition allows for the linkage to nonlinear material packages thus enabling an exact implementation of the finite strain based material nonlinearity irrespective of the type of the finite element.

ARMA 15-0111

Discrete Element modeling and analysis of shielding effects during the crushing of a grain

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Shielding is defined as the phenomenon by which small particles act as coating agent and prevent larger particles from crushing. Coating particles are typically at least one order of magnitude smaller than the large, crushable particles. The shielding mechanism can be explained by the redistribution of concentrated compression forces at particle contacts into a distributed pressure that is close to hydrostatic conditions. Hence, a large crushable particle is protected by shielding only if its coordination number exceeds a critical value. Below this so called “shielding coordination number”, increasing the coordination number of a particle embedded in a granular assembly subject to compression enhances crushing. Above this critical value, the trend is reversed: the resulting compression force necessary to break the particle decreases with the coordination number.

In this paper, we determine the shielding coordination number of a sand particle subject to a finite number of compression forces. We model the sand particle as a spherical cluster of bonded, hexagonally packed, equally sized, non-breakable spheres with the Discrete Element Method (DEM). The compression forces applied by neighboring particles are accounted for by applying velocity boundary conditions to walls. The evolution of the total compression force applied at the cluster/wall contacts with the displacement imposed to the walls allows us to determine the minimum number of contacts necessary to ensure the shielding of the sand particle.

First, we simulate uniaxial compression tests by using two walls, and we calibrate our DEM cluster model against published force/displacement curves obtained during experimental tests. We also benchmark our numerical model with another DEM model of crushable sand particle, in which the cluster is not spherical. Then, we describe the procedure employed in DEM to increase the number of walls from two to six, eight, twelve and sixteen in 3D. Next, we explain the methodology to generate a random distribution of walls. We present the corresponding force displacement curves obtained during the crushing simulations. Lastly, we present the variations of the total resulting compression force applied by the walls with the coordination number, and determine the shielding coordination number. We expect that our computational method will allow the enhancement of crushing in powder technology, and the prevention of crushing in geotechnical engineering.
Keywords: Discrete Element Method, uniaxial compression, particle crushing, shielding effects, coordination number

ARMA 15-0302

Verification of the implementation of rock-reinforcement elements in numerical analyses based on the hybrid combined finite-discrete element method (FDEM)

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Numerical simulations are widely adopted in the design of several types of rock structures, including tunnels, caverns, rock cuts, and open pit and underground mines. In recent years, analyses based on the hybrid finite-discrete element method (FDEM) have been shown to provide a realistic representation of rock mass deformation and fracturing processes (Mahabadi et al. 2012; Lisjak et al. 2014a; Lisjak et al. 2014b). Through a collaborative research effort between Geomechanica Inc. and Queen's University, an implementation of linear rock reinforcement elements has been recently developed to extend the applicability of the FDEM method to a wider scope of rock engineering problems.

The implemented approach represents an adaptation of the reinforcement elements developed for FDEM analysis of reinforced concrete (Zivaljic et al. 2013). To date, a significant effort has been made in verifying that the implemented reinforcement elements function as expected when subjected to simple axial loading (i.e., pull-out test) (Tatone et al. 2015). However, the behaviour of these elements under more complex loading configurations has yet to be verified (i.e., shear loading and combined axial-shear loading). Therefore, the objective of the current paper is to present the results of selected verification modelling that demonstrates how the implemented rock reinforcement behaves when loaded in shear. The model geometries are consistent with those adopted by Grasselli (2005) in order to test the shear behaviour of grouted rock bolts in the laboratory. Based on the results, the limitations of the implemented approach are identified and possible future improvements are discussed.

These systematic verification activities represent an important further step towards developing a simulation tool that can be used in practical rock engineering applications, including the design of underground excavations and rock slopes.

ARMA 15-0536

Parametric study of smooth joint parameters on the behavior of inherently anisotropic rock under uniaxial compression condition

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Inherently anisotropic rocks are modelled under uniaxial compression condition with the use of two-dimensional Discrete Element Methods (DEM). To represent the inherently anisotropic rock, the rock matrix is modeled as an assembly of rigid particles and the existence of weak layers is directly represented by imposing individual smooth joint (SJ) contacts into the rock matrix with the same orientation. The properties of a SJ contact include normal and shear stiffness, normal strength, cohesion and friction angle. A systematic study is conducted to investigate the influence of these

parameters on the macro behaviors of anisotropic rocks with different anisotropy angles. Young's modulus significantly increases with the SJ normal stiffness when the anisotropy angle is low (0°-30°). USC will increase with the SJ normal strength at high anisotropy angle ($\beta > 60°$) while cohesion will increase the UCS at medium anisotropy angle (30°-60°). The influence of friction angle is not significant. Understanding the influence of each parameter is of great importance for the calibration of micro parameters to represent certain type of rock. A general process for the calibration of micro parameters to reproduce the strength and deformation behaviors of different types of anisotropic rocks is proposed.

Keywords: DEM; smooth joint contact; inherently anisotropic rock; parametric study

Technical Session 31 – Elizabethan AB
Acoustic Emissions: Fracture Monitoring from Laboratory to Field Scale

Tuesday, June 30, 2015, 04:30 pm - 06:00 pm

Chairs: Steve Glaser & Sergey Stanchits

ARMA 15-0204

Calibrated acoustic emission system records M -3.5 to M -8 events generated on a saw-cut granite sample

Gregory McLaskey[1], David Lockner[2]

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Acoustic emission (AE) analyses have been used for decades for rock mechanics testing, but because AE systems are not typically calibrated, the absolute sizes of dynamic microcrack growth and other physical processes responsible for the generation of AEs are poorly constrained. We describe a calibration technique for the AE recording system as a whole (transducers + amplifiers + digitizers + sample + loading frame) that uses the impact of a tiny ball as a reference source. We demonstrate the technique on a 76 mm diameter cylinder of westerly granite loaded in a triaxial deformation apparatus at 40 MPa confining pressure. In this case, a 4.76 mm diameter ball is dropped with the aid of a magnet inside a cavity within the sample while inside the pressure vessel. We compare this reference source to conventional AEs generated during shear loading of a saw-cut simulated fault in a granite sample at confining pressures up to 120 MPa. All AEs occur on the saw-cut surface and have moments from **M** -5.5 down to at least **M** -8, while stick-slip events that rupture the entire simulated fault radiate seismic waves similar to those from a **M** -3.5 earthquake. The largest AE events that do not rupture the entire fault are **M** -5.5. For these events, we also estimate the corner frequency (200-300 kHz), and we assume the Brune earthquake source model to estimate source dimensions of 4-6 mm. These AE sources are larger than the 0.2 mm grain size and smaller than the 76 x 152 mm fault surface. Finally, we compare our results to other calibrated AE studies performed on different loading machines and discuss reasons for the observed maximum AE magnitude.

ARMA 15-0134

What can we learn from ultrasonic velocities monitoring during hydraulic fracturing of tight shale

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Methods of prediction the size and aperture of created hydraulic fracture are essential for a proper design of unconventional reservoir well stimulation. Several theoretical models describing hydraulic fracture propagation have been developed. However, there is a lack of direct field measurements of hydraulic fracture dimensions, verifying results of these models. Monitoring of elastic wave parameters may be a useful tool to estimate fracture dimensions. Indeed, the elastic wave velocity in a medium containing a fracture is sensitive to the fracture geometry and its conditions: dry fracture or saturated with fluid.

In this paper, we focus on ultrasonic velocities monitoring during hydraulic fracturing of tight shale. We report the results of hydraulic fracturing of Niobrara shale outcrop block of 279 x 279 x 381 mm size from Colorado, USA [Stanchits et al. 2012]. In this experiment, the block was loaded in a polyaxial loading frame made by TerraTek, a Schlumberger Company. Stresses were applied to the rock blocks independently in three directions using flat jacks. Then viscous fluid was injected into borehole at a constant flow rate. 20 PZT sensors were embedded into pockets drilled in the rock. They were used for registration of Acoustic Emission (AE) signals and for periodical ultrasonic transmissions to measure P-wave velocities in different directions.
Our results show that ultrasonic measurements can be useful for understanding the mechanics of the crack growth. More precisely, from the evolution of the P-velocities and their amplitudes during the loading, we are able: (i) to estimate the velocity of the hydraulic fracture which was found to be 0.15 mm/s (that is close to the fracture velocity inferred from the dynamic of AE spatial evolution). (ii) In addition, the evolution of the P-velocities during the loading shows that a liquid-free crack always precedes the liquid front. In our experiment, the lag is estimated to be 15 mm. (iii) Finally, at fixed distances from the borehole, we were able to predict the aperture of the hydraulic fracture, and its evolution during the loading. For example, at 10 cm from the borehole, the aperture reaches a value of 1mm at the moment of wellbore pressure breakdown and decrease slightly down to 0.9 mm during fluid pressure drop.
These results shows that ultrasonic velocities monitoring can yield direct measurements of fracture width, length and dynamic of propagation. These inferred properties of the hydraulic fracture can also provide verification of the results of various theoretical models describing fracture propagation.

ARMA 15-0069

Acoustic Emission monitoring of laboratory scale hydraulic fracturing experiments

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Hydraulic Fracturing type experiments on 150 mm edge length cube shaped blocks with a 13 mm diameter central borehole under different true-triaxial confining pressures up to 7.5 MPa have been conducted in this study. The tests lead to the initiation and propagation of new fractures and the interaction of those with pre-existing zones of weakness. Rock types that have been tested comprise rhyolites, sandstones and slates with generally low porosity and permeability. The sandstones and rhyolites contain natural pre-existing fractures that are healed in the case of the rhyolites. Fracturing has been conducted with water as a fracturing fluid (FF) by an open-hole packer system. In a second study fracturing was achieved via pressurization of an elastic polymer sleeve (SF) in the borehole to eliminate poroelastic effects. Pressurization rate of the borehole was around 0.3 MPa per second. Main focus of one part of this study, as presented here, is the non-destructive mapping of the fracture development by means of Acoustic Emission (AE) monitoring. AE data were evaluated using a self-written program based on actual AE-processing techniques. A total of 40 experiments containing different true-triaxial loading conditions have been evaluated.
AE data evaluation revealed several characteristics of fracture initiation, propagation and associated AE attributes. During far-field stress loading pre-existing fractures inside the samples started to emit AE. These localizations revealed the structure of the pre-existing fractures that yield important information for the interpretation of the subsequent fracture propagation. In the case of the FF experiments, the fracture propagation velocity was too fast to be monitored in detail what can be directly related to the viscosity of the fracturing fluid and the AE sensor characteristics. The SF experiments, on the other hand, could be monitored very precise. This can be attributed to the much lower fracture propagation velocity that is caused by stable fracture propagation. AE monitoring also revealed 'trapping' and 'deflection' of the induced fractures at pre-existing fractures. Branching and deviation of the induced fracture away from the expected orientation as well as fracture propagation parallel to the borehole became visible after AE evaluation in some experiments. Also the activation of pre-existing fractures prior to fracture initiation and different kinds of fracture initiation patterns were observable. In some special cases of the sleeve fracturing experiments super fast fracture propagation was observed with fracture propagation velocities higher then those observed during the

water fracturing experiments (FF). A simple AE source type analysis revealed differences in source type relations for fracture reopening, fracture propagation and fracture closure. AE monitoring during the experiments conducted at the slates were accompanied with several lithology related issues that reduced the applicability of AE as a measurement tool.
AE monitoring of hydraulic fracturing experiments revealed the complexity of this kind of experiments even under laboratory conditions. It turned out that the AE results are relevant for the interpretation of the hydraulic and deformation data acquired during the tests. The ability to deliver an estimate of the fracture initiation pressure and to map the fracture geometry in time are important information for modeling and model verification that are also conducted in another part of the same project.

Figure 1: AE localizations color-coded in time for two exemplary SF-type experiments. S1, S2 and S3 represent the directions of the three external loadings, respectively with S1>S2>S3. The left hand plots show the curved deviation of an induced fracture. The plots on the right hand side show the pre-existing fracture network becoming visible by AE (blue events) together with the induced fracture (blue and red events).

ARMA 15-0502

Observations of Acoustic Emissions in a Hydraulically Loaded Granite Specimen

Bing Q. Li[1], Zabihallah Moradian[1], Bruno Goncalves da Silva[1], John Germaine[1]
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Hydraulic fracturing has become increasingly prevalent in the oil and gas industry as well as in enhanced geothermal systems as a method to increase the permeability of rock masses. However, the process is still not very well understood in terms of the fracture mechanisms that occur as cracks initiate, propagate and coalesce. Microseismic investigations by means of acoustic emissions during laboratory tests can be useful in this regard as they provide insights into fracture behaviour during hydraulic loading under controlled conditions.
This paper describes the development of an acoustic emissions setup capable of capturing a stream of data over approximately 5 seconds corresponding to crack initiation, propagation and coalescence. The challenge is that acoustic emissions system are typically designed to capture burst data, where emissions are far enough in between for the system to re-arm. However, close to the time of crack initiation the hit rate tends to increase to the point where effectively a continuous signal is observed by the sensors, resulting in saturation of the system due to data overload.
Areas explored in this paper include: the relation between the AE timing parameters of hit definition time (HDT), hit lockout time (HLT) and maximum duration; the use of a floating threshold and front end filters to limit data input into the system; and the scaling of computational load from increasing the number of sensors and the sampling rate. The hardware requirements in terms of system resources such as CPU, hard drive speed and RAM are also explored.
Acoustic emissions data captured using such a setup is presented for a granite specimen hydraulically loaded to failure. Localisation and event characterisation are compared to high speed and high resolution imagery captured for the same test.

ARMA 15-0239

AE-Rate Controlled Mode II Fracture Propagation Experiments on Granite and Sandstone

Marc Rück[1], Roman Rahner[1], Hiroki Sone[1], Georg Dresen[1]
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We studied the initiation and propagation of mode II fractures in granite and sandstone under confining pressure to investigate the controls on shear fracture propagation in rocks. Experimental outcomes based on acoustic emission (AE) observations are presented which show the different fracture nucleation and propagation behaviour observed between granite and sandstone. An asymmetric loading test was used to induce a discrete shear fracture under confining pressure between 0-20 MPa. 80% of the top face of each cylindrical specimen was covered with a steel plate which acted as a stress concentrator. An AE-sensor registered the emission rate and was used as feedback signal to control the axial displacement. This allowed stabilizing fracture propagation extending from seconds to several hours. The fracture initiation and propagation process was monitored by located AE-hypocentres recorded by twelve piezoceramic sensors attached to the sample surface. The AE-events were also categorized into 3 source types, tensile- (T-type), shear- (S-type) and compaction- (C-type) events, based on the statistics of first motion polarity captured by the AE-sensors. For the granite experiments first a stable vertical fracture was produced below the stress concentrator as the axial load was increased. A second diagonal fracture developed as the rock failed and lost its load-bearing capacity. In contrast, in the sandstone experiments, a diagonal fracture was produced without the formation of a vertical fracture. Analysis of the first motion polarity showed that in all experiments, S-type events dominated the process after fracture initiation, as expected from the overall mode II loading conditions. However, many C- and T-type events accompanied the S-type events reflecting the complex geometry of the fracture propagation process. We also observed that C-type events were concentrated below the edge of the steel plate in the sandstone experiments before the peak stress which was not evident for the granite experiments. Influence of confining pressure was also different between rock types. With increasing confining pressure, we found an increase in the amount of T-type events for sandstone whereas an increase in the amount of C-type events was observed for granite. Our experiments show that the differences in rock properties cause vastly different fracture propagation behaviour. We interpret that the C-type events that occurred in the sandstone experiment below the stress concentrator helped to lower the cohesion of the rock, and thus the shear strength, which allowed the formation of diagonal fractures without the vertical fractures in the sandstones.

ARMA 15-0474

Micro-Seismic Monitoring of PDC Bit

Yingjian Xiao[1], Jinghan Zhong[1], Charles Hurich[1], Stephen D. Butt[1]
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Drilling Performance during Vibration Assisted Rotational Drilling

This study is an evaluation of the feasibility of real-time drilling performance monitoring using a near-bit AE detection tool. A new Vibration Assisted Rotational Drilling (VARD) tool was manufactured and tested aiming at increasing drilling performance with PDC drag bits under laboratory and field conditions. This paper focuses on calibrating the micro-seismic response to rock failure mechanisms in relation to shear and tensile cracking and a study of the mechanisms of improved Rate of Penetration (ROP) on the basis of rock mechanics. Synthetic concrete cylinders with comparable properties to natural rock were fabricated in the laboratory. Drill-Off Tests (DOT) were conducted under conditions of rigid and vibration drilling with a two-cutter PDC bit. Meanwhile, micro-crack Acoustic Emissions (AE) from the bit-rock interaction process were monitored by four symmetrically mounted Non-Destructive Testing (NDT) sensors. The fracture mode was investigated by analyzing acoustic events of micro-cracks from inside the concrete and the micro-seismic properties of the events were interpreted in terms of event occurrence patterns, dominant frequencies, and event energies. Analysis from the DOT indicated some factors associated with improved drilling performance, including the rock fracture mode, axial vibration, AE parameters and the grain size distribution of cuttings. Also, the grain size of cuttings, indicating cutting depths and crack dimensions, correlated with the positive influence of vibration on ROP. Simultaneously, axial vibration parameters, such as magnitude and frequency, were correlated to the AE analysis and the grain size distribution of cuttings. All of this has contributed to our understanding of the mechanisms of improved drilling performance.

Key words: Acoustic emission; Vibration drilling; Rock mechanics; ROP; Synthetic concrete; Rock failure mechanism; Drill-off test; PDC bit; Bit-rock interaction; Drilling performance; Cutting grain size; Vibration assisted rotational drilling

Technical Session 32 – Elizabethan CD
Coal Mining Ground Control
Tuesday, June 30, 2015, 04:30 pm - 06:00 pm

Chairs: Erik Westman & Samrat Mohanty

ARMA 15-0846

Numerical Modelling of Roof Support Plans at 4-Way Coal Mine Intersections

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About 80% of the roof falls in the USA occur at intersections. Over the last few years, SIUC researchers have launched research efforts to improve stability of intersections. Chugh and Behrooz (2010) performed numerical analyses of an idealized 4-way intersection typical in the Interior Basin longwall coal mines to develop a better understanding of stress and displacement redistributions around an intersection. That research was followed by similar analyses around physically realistic irregular intersection geometries in development and setup rooms (Bastola, Corbin, Behrooz and Chugh, 2012). Both these studies identified need for alternate support systems around an intersection. Some of the developed concepts were successfully demonstrated in the field using standing supports at intersection corners.

This research analyzes the performance of several different roof support plans with primary and secondary supports. The plans include some that are currently practiced and others that were developed in cooperation with industry and bolt suppliers. All plans are considered operationally viable and cost effective. These plans also incorporate principal author's concepts for improved roof support around intersections. The authors believe that the current support plans do not reinforce the immediate roof rock mass and allows the rock mass to go into dilation phase over time leading to roof falls. The support density is not spatially adequate to provide roof stability. The authors' hypothesize that the immediate roof should be provided with high initial stiffness supports around the pillar corners so that the load is transferred deeper into the solid pillar and then into the floor strata through coal pillars to minimize progressive yielding of pillar corners. Rock mass around the centre of the intersection needs to be reinforced as well as suspended from competent strata above. Three-dimensional numerical analyses using FLAC were performed for different support plans. Rock mass engineering parameters were developed using estimated values of GSI and Hoek-Brown estimates for different lithologies in the immediate roof and floor strata. Numerical models include recently developed normal and shear stiffness parameters for the immediate roof strata. Analyses attempt to quantify reinforcement provided by different roof support plans through analyses of yielded zones and mechanisms of failure in each zone.

ARMA 15-0138

Rapid assessment of roof stability in coal mine entries based on the outcome of validated numerical models

Gabriel Esterhuizen[1], Berk Tulu[1]

[1]*NIOSH*

Numerical modeling procedures have been developed at NIOSH for evaluating roof stability in coal mine entries. The models simulate the response of supported entries under various loading and ground conditions using Itasca's FLAC3D software. A useful outcome of the models is a 'stability factor' that indicates the stability of the roof of the entry against collapse. The stability factor is determined through successive reductions in the modelled rock strength until collapse is indicated, known as the strength reduction method. The model results have been calibrated against field measurements and extensive validation studies have been conducted to verify that the models provide realistic stability estimates of entries in operating mines (Published in2013).

Conducting numerical model analyses can be time consuming, requires special software, and requires specialist expertise for setting up models and evaluating the results. However, it is possible to develop a prediction equation that estimates roof stability based on the single 'stability factor' (SF)

outcome of the numerical models. The SF outcomes of more than 500 numerical models of entries in ground conditions, depths of cover, stress conditions, and support systems that might be encountered in US coal mines were used to develop a prediction equation. Least squares curve fitting procedures were used to find the unknown parameters of a nonlinear equation of the form:

$SF = k \times S^{\alpha} \times R^{\beta} \times W^{\delta}$

Where: k is a constant, and α, β, and δ are unknown exponents determined by least squares curve fitting. S is a parameter representing support efficiency which is a combination of support length, spacing and anchorage capacity. R is a parameter representing rock mass stability which is based on the ratio of the rock mass strength to vertical and horizontal stress. W is the entry width. The composition of the S, R and W parameters were developed from regression analyses, inspection of modeling results, and observation based understanding of roof failure at field sites.

The developed equation shows excellent correlation with model calculated SF values. The overall coefficient of determination (r^2) is 93. The relationship between model results and equation predicted SF values for complex geologies, consisting of weak and strong roof beds that produce a wide range of outcomes depending on support length.

The developed equation can be used by practitioners to conduct a quick assessment of likely roof stability for a range of conditions using spreadsheet software, without the need for specialized numerical model analysis. Detailed information on support response, rock damage and mechanism of collapse is obviously not available when conducting a simple equation based analysis

ARMA 15-0241

Calculating Potential Coal Pillar Bumps Using a Local Mine Stiffness Criterion

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Coal mine bumps are a serious safety problem in coal mines and they are very hard to predict due to the uncertain mechanics of this dynamic failure phenomena. However, previous research has demonstrated that the local mine stiffness criterion is a promising approach for analyzing the possibility of violent pillar failure. Typically, the local mine stiffness calculation quantifies the loading stiffness of the surrounding rock mass and compares that to the stiffness of the support pillars in the post-failure range in order to determine if a failure in the mine will occur in a stable or un-stable manner. If the loading stiffness is softer than the support stiffness, a dynamic failure can occur. With this knowledge ahead of time, the mine engineers can modify the geometries and pillar sizes in the mine design to eliminate violent pillar failure.

In this paper, the principles of the local mine stiffness criterion are reviewed. Also, previous research on the strain-softening behavior of coal pillars, the stiffness behavior of the surrounding rock mass, and the factors which influence these behaviors are reviewed and analyzed. Then, an actual coal mine, pillar bump accident is back analyzed with the LaModel code with a recently implemented local mine stiffness calculation. The numerical model was initially calibrated to thoroughly match the observed mine failure, and then the local mine stiffness and post-failure pillar stiffness were calculated and compared. In this mine model, the mine stiffness steadily decreased to eventually match the pillar stiffness at the time of the observed violent failure. This case study demonstrated that the local mine stiffness criteria can be successfully calculated and applied, but the accuracy of the calculation is very dependent on accurate material properties, mining progress and other model parameters.

ARMA 15-0497

Coal mine pillar failure patterns explained through probabilistic analysis

Tawanda Zvarivadza[1]

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Probability and risk in rock engineering is one of the powerful rock engineering tools for solving problems. This tool adopts a probabilistic theory in giving a solution to a problem through the analysis of field observations. Probability and risk make use of approaches such as Monte Carlo

simulation, first order second moment analysis, fault tree diagrams among others. Through these approaches one can clear a misconception people may have on a problem. In some instances the probabilistic analysis bring more light to the extent of dismissing (step by step) an argument which would have seem to be originally reasonable (like in this paper).
This paper is based on a Monte Carlo simulation of a problem where a coal mine is divided into two sections (east and west) by a dyke such that the east section experiences no pillar failures while the west does despite having the same safety factor. This may prompt one to mine the east section at a lower safety factor arguing that the east section must be logically stronger compared to the west section. The simulation undertaken utilises observations of road width, mining height and mining depth for both sections. A sensitivity analysis was carried out in order to select the most appropriate formula for solving the problem between the power formula and the linear formula. The linear formula was considered to be the best as it gave the same stability as the power formula but enabling mining to smaller pillar size. This enables stable, safe and sustainable utilisation of mineral resources. A detailed analysis was then done to assess both sections using the linear formula. It is the finding of this analysis that contrary to one's argument, both sections are over designed with actually the west section, which is failure ridden, being more over designed than the east section. This is because higher safety factors were encountered for the west section compared to the east section. The failures of pillars in the west section were attributed to greater variability in mining variables in the west section compared to east. The east suffers no failure although it has lower safety factors because it is more uniform and less variable such that load is uniformly distributed among pillars without stress concentrations like in the west section.
The paper recommends that the mine shift to the use of the linear formula and mine both sections to a safety factor of 1.6 while ensuring uniformity of the mining variables. In other words the mining layout for both sections must be as uniform as possible.

ARMA 15-0240

Ground control in China's coal mine: progress and prospects

Jiachen Wang[1], Jinwang Zhang[1], Yang Li[1]
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Abstract: Coal is China's main energy sources, accounting for about 70 percent of China's primary energy consumption. China is the world's largest coal-producing country and its coal production was 3.8 billion ton in 2013, which accounts for 48 percent of the world production. In China, underground mining accounts for more than 85% of the total production, so it plays an important role in China's coal industry.
Because of the diversity and complexity of coal occurrence conditions, there are a variety of methods in underground mining in China. These methods are mainly as follows: (1) General longwall mining method (mining height is between 1.5m~3.5m). (2) Large mining height method (mining height is larger than 3.5m). (3) Top-coal caving mining method (one passing mining for coal seams whose thickness is larger than 6m). (4) Thin bedrock mining method. (5) Steeply dipping seam mining (seam dip angle is larger than 35°). Diversity of mining methods would inevitably lead to the diversity of ground control technique. Based on China's coal mining situation, this paper mainly introduced progress and prospects of ground control theory and technique in China's coal mine over the past decade.

1. Progress in basic theory of ground control
This part mainly introduces the "Voussoir Beam" theory, "Key Strata" theory, dynamic theory for determining the supports capacity, relationship between supports capacity and coal wall stability, loose medium flow field theory of longwall top-coal caving and thin bedrock mining theory.
2. Strata control of working face roof
This part mainly introduces basic methods of strata control in working face, including development process and current situation of hydraulic support, different supports and strata control situation in different coal seams such as thin seam, medium-thick seam, thick seam using large mining height method and thick seam using top-coal caving mining method.

3. Roadway control technique
This part mainly introduces progress in bolt support technique, bolt and anchor combined support technique.
4. Surface deformation control and filling mining technique
This part mainly introduces the development and application of three different filling mining techniques and strip mining method in China.
5. Prospects of ground control in China's coal mine
Based on China's coal mining technical progress, main directions of future development of ground control theory and technique in China's coal mine were proposed.

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Technical Session 33 – California West
Wellbore & Drilling Mechanics 1

Wednesday, July 1, 2015, 08:00 am - 09:30 am

Chairs: Maurice Dusseault & Andy Tallin

ARMA 15-0366

Wellbore Stability Modeling with a Grain Based Rock Model

Fengshou (Frank) Zhang[1], BT Lee[1], Mark Mack[1]
[1]*IMaGE*

A new grain based rock model was developed and applied to study the wellbore stability problem. The model mimics the rock as an assembly of tetrahedral blocks with bonded contacts. Material heterogeneity can be achieved by assigning different tensile strength at the block contacts. This grain based rock model differs from the previous disk/sphere particle-based rock models (e.g., Potyondy and Cundall, 2004) in its ability to represent a zero (or very low) initial porosity condition, as well as highly interlocked irregular block shapes that provide resistance to moment even after contact breakage. As a result, this model can reach a higher uniaxial compressive strength to tensile strength ratios and larger friction coefficient than the disk/sphere particle-based rock model.
The model was firstly used to match the properties of typical rocks (such as sandstone) by using the direct tension test, uniaxial compression test, and toughness test. Then the calibrated model is applied to study the wellbore breakout test and the thick-walled cylinder (TWC) test. The model showed the fragmentation process near the wellbore due to the buckling and spalling. Thin fragments of rock similar to onion skins were produced which were seen in the lab breakout experiments (e.g., Haimson, 2007). In general, the results of testing to date suggest that the approach may be well-suited to study the rock disaggregation process and with great potential for many geomechanical problem in the oil and gas industry.

ARMA 15-0082

An Integrated Analytical Workflow for Analyzing Wellbore Stress, Stability and Strengthening

Mojtaba P. Shahri[1], Reza Safari[1], Moji Karimi[1], Uno Mutlu[1]
[1]*Weatherford*

Lost circulation is one of the largest contributors to non-productive time in drilling operations. This is particularly true for wells being drilled in complex geological settings such as deep water or highly depleted zones/intervals. Several geomechanical mechanisms (e.g., near wellbore fracture propagation, thermo-poroelastic processes, mud cake formation, etc.) can act together and control lost circulation risk. Therefore, one of the prerequisites for a successful design is to establish a workflow that integrates multiple mechanisms within the framework of a geomechanical engine.

Based on current industry design, predicting the safe mud weight window (MWW) for a depleted interval usually involves time-independent linear elastic models. These elastic/ steady-state models can't take into account transient temperature and mud cake effects as observed during drilling operations. In addition, most fracture based strengthening workflows are decoupled from stress and stability analysis. That is, near wellbore stress perturbations are not considered in fracture initiation and propagation calculations and can lead to unrealistic induced fracture width/length predictions. We show that, by utilizing a fully transient thermo-poro-elastic model, the external/internal mud cake and temperature effects on the near-wellbore stresses and stability can be predicted accurately. Accordingly, and based on the stress/stability calculations, an integrated approach allows us to quantify the impact of multiple strengthening mechanisms on: (i) MWW (ii) Fracture gradient or fracture re-initiation pressure (iii) induced fracture characteristics (via a coupled near wellbore fracture simulation module).

The aim of this study is to present an integrated and analytical workflow which includes the following execution steps: 1) generating a geomechanical model for the wellbore based on input data from different sources; 2) determining the stress tensor around the wellbore based on a transient thermo-poro-elastic model which include internal/external mud cake effects; 3) determining the drilling safe mud weight window based on various failure criteria; 4) identifying troublesome zones with narrow mud weight window throughout the well trajectory; 5) performing an integrated wellbore strengthening analysis based on different mechanisms (e.g., fracture propagation, fracture plugging, thermal, external and internal mud cake effects); 6) performing an integrated mud loss volume prediction using different mechanisms (e.g., natural fracture loss, induced fracture loss, formation loss); and 7) quantifying the amount of strengthening and re-generating mud weight window for safe drilling. The integrated tool provides a suitable workflow when drilling through depleted zones and for lost circulation.

ARMA 15-0152

Hidden Impact of Mud Loss on Wellbore State of Stresses Disclosed by Thermal-Poro-Elastic Modeling

Yuanhang Chen[1], Mengjiao Yu[1], Nicholas Takach[1], Zhaorui Shi[1], Chao Gao[1]
[1] *University of Tulsa*

The thermal regime of a formation in the vicinity of a wellbore affects the stability of the well significantly during drilling operations, especially for deeper or geothermal wells. This paper presents how the thermal behavior of a wellbore varies with time during mud loss, and its consequent impact on wellbore stability. A new coupled 3D thermal-poro-elastic model, integrated with a transient wellbore thermal model, is developed to evaluate the stress and pore pressure redistribution after a mud loss. The model allows the introduction of mud loss under various conditions. The result of a simulation reveals that mud loss induces reduction in temperature of mud as well as the formation in the lower section of the wellbore. Results also show that continuous mud loss destabilizes the near-wall region as the fracturing gradient decreases. This can intensify the existing fracturing condition and allows the development of new fractures, which leads to further mud loss as time progresses. During severe loss, the fracture gradient at the bottom of the well can decrease by over 1 ppg within the first few hours. The change in critical mud weight window with time under different lost circulation conditions and with different types of muds (OBM/WBM) are presented to quantify the effect. Other factors such as inclination angle, anisotropic field stresses, and change in mud inlet temperature due to the addition of new mud during the loss are also evaluated in this work. This model allows prediction of a more realistic operating window during lost circulation by taking thermal effects into account. It is of practical significance for evaluation of the effect of time on lost circulation and the states of stresses when using different types of mud.

ARMA 15-0048

Application of Rock Physics in Wellbore Stability Modeling for Chayvo Field Multi-lateral ERD Wells

Shekhar Gosavi[1], Steinar Ottesen[1], Shea Sanford[1], Randall Mathis[2], Shiyu Xu[3]

[1]ExxonMobil Development Company, [2]Exxon Neftegas Limited, [3]ExxonMobil Exploration Company

In 2013, the Chayvo field drilling program marked its 10th anniversary with a new world record ERD well (measured depth 12,700 m) and by successfully drilling and completing Russia's most complex offshore multi-lateral ERD well. Multilateral technology enables increased production from a single well by drilling one or more additional boreholes into the reservoir from the original wellbore.

A large number of challenging ERD wells had already been successfully drilled in the Chayvo field using non-aqueous drilling fluid (NADF) and stability mud weights determined by wellbore stability modeling. The original wellbore stability model was based on local in-situ stresses, logs and shale surface area rock strength correlations; calibrated and validated against field experience. Compared to the original Chayvo ERD wells, one significant challenge in drilling the Chayvo multilateral wells was a reduced margin between the required higher stability mud weights and the depleted formation fracture gradient due to less favorable borehole azimuth and reservoir depletion, respectively. Additionally, a high quality borehole was required for installation of the complex multilateral equipment. More accurate and reliable well-specific rock characterization was therefore desirable to enable determining well-specific minimum acceptable stability mud weights to successfully drill these complex multi-lateral ERD wells.

The existing main horizontal boreholes through the sandstone and shale sequences of the reservoir anticline provided good geologic and lithological control for the planned horizontal multilateral boreholes. The challenge was to come up with a reliable method of determining the rock strength along the horizontal boreholes, as sonic logs and/or shale surface area data was sparse. However, LWD density and gamma ray logs were readily available and the rock physics methodology described in this paper provides a well-specific characterization of rock strength when limited sonic log data is available. This methodology ultimately generates a synthetic sonic log using rock physics models calibrated to available sonic data from analogous wells. As demonstrated in this paper, these synthetic sonic logs proved to be a reliable basis for rock strength determination in wellbore stability modeling and were incorporated into the Integrated Hole Quality and Quantitative Risk Assessment (IHQ/QRA) technology to determine the optimum mud weights for the Chayvo horizontal multi-lateral boreholes, considering wellbore stability, hydraulics, hole cleaning and lost returns. Actual field drilling performance, observed borehole quality, and available log data from both donor and analogous wells have also been used to calibrate and validate the rock physics models as well as the Chayvo field earth model.

This paper presents how the rock physics derived rock strength was incorporated into the current IHQ/QRA workflow, resulting in increased accuracy and reduced uncertainty in borehole breakout and stability mud-weight predictions, respectively, for the Chayvo multilateral wells.

ARMA 15-0174

Characteristics of mechanical wellbore failure and damage: Insights of discrete element modelling and application to CO_2 storage

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Failure and damage of wellbores and rocks surrounding wellbores have widespread implications for drilling, completion, integrity and abandonment of wells. The drilling and completion of wells may cause significant damage in rock masses surrounding the wellbore. Damage may include borehole breakouts and drilling induced fractures with characteristic properties that are dependent on properties of rock and drilling mud as well as local stress field. These characteristic properties are often used to determine the orientation and magnitude of the maximum horizontal stress. For completed or abandoned wells, different parts (e.g., cement sheath and casing) may be damaged due to subsurface stress changes or deformation resulting from injection or depletion activities, which may ultimately lead to loss of well integrity. Well integrity is particularly important for subsurface storage of CO_2, where integrity of abandoned wells has to be ensured over long time scales of 100's to 1000's of years.

In this study three dimensional discrete element models of wellbore systems have been used to simulate failure and damage of wellbore cement and surrounding rock. The aim is twofold, focussing on the derivation of (1) relations between rock properties, local stress field and characteristics of wellbore breakouts and induced fractures during drilling, and (2) critical stress conditions for wellbore failure and associated damage leading to loss of well integrity during reservoir injection or depletion. The models allow simulation of wellbore failure and damage in both centralized and non-centralized completed wellbores, both plugged and open wellbores, and both idealized or imperfect plug-casing-cement sheath-rock interfaces. In addition, both axial and radial wellbore failure can be simulated.

A sensitivity study of breakout and induced fracture properties for ranges in rock properties and stress conditions is used to compare model simulations with theoretical models, and identify conditions for which results may deviate from theoretical predictions. Comparison between conditions of failure for completed wellbores and constraints on stress conditions around wellbores in real field cases is performed. The analysis determines the feasibility of (1) upward CO_2 migration through wellbore cement or along cement-rock interfaces past natural migration barriers due to alignment of fractures and the formation of connected fracture network, and (2) radial and axial wellbore failure under different injection and depletion conditions. The results are used to map out the subsurface conditions for which wellbore failure and damage of wellbore cement may occur.

ARMA 15-0431

Effects of Adsorptive Characteristics of Shale on Wellbore Stability

Vahid Dokhani[1], Mengjiao Yu[1], Stefan Miska[1], Nicholas Takach[1], Evren Ozbayoglu[1], Ben Bloys[2]
[1]University of Tulsa, [2]Chevron Corporation

The interactions between an aqueous drilling fluid and clay minerals have been recognized as one of the important factors in wellbore instability of shale formations. Current wellbore stability models describe the interactions between the drilling fluid and pore fluid and the interactions between the aqueous fluid and shale matrix is often neglected. There are some experimental studies in the literature that focused on the adsorption properties of shale rocks, while few attempts have been made to model the phenomenon. We initially conducted laboratory experiments on samples of Mancos shale and Catoosa shale to examine their adsorptive properties. Our primary conclusion is that the clay content is correlate with the amount of sorbed water to the pore space. The experimental results show that the moisture content of shale is correlated with water activity using a multilayer adsorption theory. It is found that the GAB model (developed by Guggenheim, Anderson and De Boer) can be used to describe the adsorption behavior of the selected shale types. The adsorption parameters can be suggested as an index to characterize different shale formations. The adsorption model can be combined with empirical correlations to update the compressive strength of shale under downhole conditions.
This study shows that the adsorption theory can be used to generalize the transport equations in order to consider the case of non-ideal solutions. The coupled transport equations are solved using an implicit finite difference method. A chemo-poro-elastic wellbore stability simulator is developed to explore the stability of shale formations. The results of this study indicate that the range of safe mud weight reduces due to the moisture adsorption. Comparisons of several compressive failure criteria indicate that stability reduction of the wellbore due to moisture transport is a common pattern regardless of the selected criteria.

Key words: adsorption isotherms, pore pressure, moisture content, and wellbore stability.

Technical Session 34 – California East
Measuring and Modeling Rock Properties
Wednesday, July 1, 2015, 08:00 am - 09:30 am
Chair: Jean Elkhoury

ARMA 15-0790

Predicting intrinsic and apparent permeabilities from pore size distribution in tight porous materials

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The purpose of this work is to achieve a better understanding of the relationship between damage, failure and the transport properties of tight porous materials. This is typically of utmost importance in the enhancement of non-conventional reservoirs or in the long-term assessment of the tightness of CO2 geological storage, vessels or containment facilities.
Many authors have looked for predictive models of porous media permeability. Pioneering work by Kozeny related the permeability to the porosity, the tortuosity and an average pore size. Usually, analyses are restricted to intrinsic permeability of the material and the evolution of the apparent permeability, with respect to the pressure gradient and to the nature of the fluid considered are left aside. This paper aims at presenting a new model capable to provide estimates of the apparent permeability directly from the PSD measurements and from the properties of the fluid to be considered. The intrinsic permeability and the evolution of the apparent permeability with mean pressure are provided by combining Darcy, Poiseuille and Knudsen laws, which represent respectively the macroscale flow, the microscale viscous flaw and the microscale diffusion flow in the porous media.
In order to achieve a porous network in the material, which is consistent with a mercury intrusion technique, random generation of pores is implemented. The technique yields a hierarchical porous network, which mimics the porous space measured experimentally.
Comparisons with experimental data acquired on mortar specimens show that the model is able to reproduce both the intrinsic and the apparent permeabilities and their evolution when the material is subjected to mechanical damage, provided the PSD are available. Test data with several types of gases compare quite well with the model.
Acknowledgment:
Financial supports from the European Research Council (grant Failflow - 27769), from the French Région Aquitaine (grant CEPAGE - 20121105002) and from the French AgglomeÌ ration CoÌ,te Basque – Adour are gratefully acknowledged.

ARMA 15-0547

Study of geomechanical properties of 3D printed sandstone analogue

Sander Osinga[1], Gonzalo Zambrano-Narvaez[1], Rick Chalaturnyk[1]
[1]University of Alberta

The validation of numerical models of geomechanical processes heavily relies on physical modelling of these processes in a laboratory setting. However, due to their heterogeneous natural, test specimens of natural materials often show a wide range of geomechanical properties. In the last decade, major advances have been made in the quality and commercial availability of 3D printers. By now, 3D printing is used in the fabrication of jet engines, medical implants and even complete buildings. This paper presents 3D sand printing as an opportunity to control many of the variables that are inherent to the study of geomaterials. A new 3D sand printer, the first of its kind in Western Canada, has been installed as part of the Foundation CMG Industrial Research Consortia in Reservoir Geomechanics for Unconventional Resources at University of Alberta. This printer uses additive manufacturing technology to print components one layer at the time from sand. By using a 3D sand printer to digitally fabricate physical models, we were able to produce multiple exact replicas of heterogeneous samples, controlling the nature of the heterogeneities and the properties of

the model matrix. Here, we present preliminary test results from uniaxial compression tests, brazilian tensile tests and triaxial compression tests on this new rock analogue material. By knowing and controlling inter-sample variability in terms of porosity, fracture networks, grain size distribution and density distribution, we have a valuable tool in hands to validate numerical models, develop scaling laws and constitutive relationships, quantify the degree of influence from pore geometry, fracture network characteristics and heterogeneity correlation structure on macroscopic properties such as bulk modulus and effective permeability.

KEYWORDS

3D Printing, Rock Analogue, Fracture Networks, inter-sample variability

ARMA 15-0504

Rate dependence of dry, oil- or water-saturated chalk

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The rate dependence of dry, oil- or water-saturated high-porosity outcrop chalk is investigated based on whether the fluid effect could be excluded from a governing material parameter, the de Waal *b*-factor[1]. The *b*-factor is used in geotechnical engineering to establish the difference in load between stress-strain curves when applying different loading rates. The material investigated is outcrop chalk from Stevns, Southern part of Denmark, with a general porosity of 43 to 44%.
The Biot critical frequency is a function of the fluid properties viscosity and density, and the material properties porosity and permeability[2]. The critical frequency is interpreted as a measure of the solid-fluid friction and hence relevant to use for subtracting the fluid effect to arrive at a pure material parameter.
The lab measurements show a correlation exists between data from dry, oil- or water-saturated chalk and a normalized Biot critical frequency.

ARMA 15-0597

Loading rate dependency of dynamic fracture toughness of rocks

Sangho Cho[1], Hyeongmin Kang[1], Minseong Kim[1], Yuzo Obara[2], Minami Kataoka[2], Kwangmin Kim[3]

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Fracture toughness is an indication of the amount of stress required to propagate a preexisting crack and is one of the most important properties of any material for many design applications such as rock drill bit, rock crushing and hydraulic fracturing in a wellbore. In this study, straight notched disk bending (SNDB) specimens of limestone and granite were used to determine the fracture toughness with wide range of loading velocity from 0.001 to 680,000 mm/min. The straight notched disk bending (SNDB) specimens were loaded dynamically with the split Hopkinson pressure bar (SHPB) system. High speed digital camera system was used to observe the fracture behavior at the tip of the notch of SNDB samples during dynamic impact loading. Static fracture toughness values of rocks were also determined to compare with the dynamic fracture toughness. The microfocus X-ray CT scanner was used to observe the microstructural damages in the vicinity of the fracture planes for the tested samples. The crack opening displacement (COD)-time histories were monitored using high speed laser displacement measurement system. The loading rate dependency of limestone and granite under dynamic loads were discussed with comparing the behavior of crack opening around the tip of the notches and high speed camera images. The mechanism of fine particles generation during crack propagation was also examined.
Keywords; fracture toughness, split Hopkinson pressure bar(SHPB), limestone, Straight Notch Disk Bending (SNDB) specimen

ARMA 15-0634

Effect of Anisotropy on Fracture Toughness and Fracturing of Rocks

Morteza Ghamgosar[1], David James Williams[1], Nazife Erarslan[1]
[1]*The Univerity of Queensland*

Abstract
Elastic properties of rocks are individually used for design purposes in open pit mining, underground spaces and rock cutting projects, however, ultimate strength of rocks are strongly influenced by microfractures, pre-existence cracks and anisotropies. Anisotropy may comprise different complex materials in nature, inhomogeneity, discontinuous, different grain sizes or shapes and indeed, orientations. Since the fracture properties of rocks is important to the geotechnical engineers concerned to design the underground or open pit mines, it is obvious that laboratory investigations on anisotropic properties are necessary for the safe designs. The main objective of this paper is investigating the effect of different anisotropy orientations of Brisbane sandstone specimens subjected to the diametral compressive loading on the fracture toughness values of those anisotropic specimens. In order to find the fracture toughness values of the anisotropic Brisbane sandstone Cracked Chevron Notch Brazilian Disc (CCNBD) specimens were prepared and tested according to the International Society for Rock Mechanics (ISRM) standards. Laboratory experiments revealed that the fracture toughness of sandstone samples are found increasing with the increasing of anisotropy orientations angle. Based on the experimental results, a statistical regression analysis was conducted to obtain the optimum orientation angle to get the highest strength under the indirect tensile loading. Statistical analysis showed anisotropy orientations between 45° and 70° give the highest fracture toughness values in the other anisotropy orientation configurations. Some of the prepared CCNBD sandstone specimens are shown in Figure 1.

Keyword Anisotropic sandstone, rock fracture toughness, CCNBD rock specimens, Statistical analysis

ARMA 15-0315

Fracture Testing in Modes I, II, and III on Escabrosa Limestone

Karen Roth[1], John Kemeny[1], Ashley Cheesman[1]
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Time-dependent rock failure is an important aspect in the analysis of long-term rock stability for slopes, dam and bridge foundations, and underground storage facilities. An on-going project at the University of Arizona is studying such failure using time-dependent fracture mechanics and subcritical crack growth modeling. Kartchner Caverns in Benson, Arizona serves as a natural analog, permitting reconstruction of the process of natural cave breakdown through LIDAR scanning, age dating of formations, and 3D damage modeling in Abaqus. Various material properties of the Escabrosa limestone composing the caverns are required for input into the damage model. Central among these properties are the subcritical crack growth parameters n and A, which can be calculated from modes I, II, and III fracture toughness tests. However, such a complete characterization with testing in all three modes is unusual. One exception is a previous study by Tae Young Ko at the University of Arizona, which tested Coconino sandstone and determined that the subcritical crack growth parameters were consistent between modes (Ko and Kemeny, 2011). This study expands upon Ko's work by adding the characterization of a second rock material in all three modes. This paper presents the results of modes I, II, and III testing on Escabrosa limestone. Tests include the grooved disc and the edge notched disc in mode I, the punch-through shear with confining pressure in mode II, and the circumferentially notched cylindrical specimen in mode III. The fracture toughness for each method is calculated, and the results are compared to fracture modeling in Abaqus. The significance of this study is twofold. First, it provides a comparison material for Coconino sandstone in order to establish whether the subcritical crack growth parameters are consistent between modes in a different rock material. Second, it provides material properties

necessary for the larger goal of modeling breakdown in Kartchner Caverns and applying the model to the long-term stability of rock excavations.

Technical Session 35 – Elizabethan AB
Failure Behavior and Constitutive Modeling

Wednesday, July 1, 2015, 08:00 am - 09:30 am

Chairs: Jeen-Shang Lin & Giuseppe Buscarnera

ARMA 15-0150

MICHELL–FOURIER ANALYTICAL TREATMENT OF STRESSES IN THE RING TEST UNDER PARABOLIC COMPRESSION

Mehdi Serati[1], David J Williams[1]

[1]*The University of Queensland*

A proper and accurate estimation of the tensile strength of a given material is a crucial step in many engineering activities; in particular in rock excavations, since rocks are much weaker in tension than in compression or shear. Both direct and indirect laboratory techniques such as the direct uniaxial tensile test, Brazilian indirect tensile test and the ring test have been proposed and developed as partial solutions to the determination of rock tensile strength. Among these, the ring test has recently attracted the attention of many researchers for its ease of sample preparation and its unique breakage mechanism in a pure tensile mode. However, the current theoretical approaches adopted for the analysis of the ring test are either restricted to uniform radial stresses applied only on the external boundary of the ring, or require excessive and sophisticated mathematical rigour in complex domains. This paper attempts to provide a simpler analytical solution in a two-dimensional elastic medium for the calculation of stress tensors induced in a ring when subjected to parabolic compression loading. The parabolic compression loading along the perimeter of the ring provides a more realistic boundary condition than uniformly distributed loading exclusively applied in previous studies (Figure 1). The parabolic stress distribution is introduced by means of the Fourier series technique, and Airy stress functions and Michell's expression in polar coordinates are invoked. Parametric studies are then performed to investigate the influence of the boundary conditions, the loading angle and the geometric characteristics of the problem on the induced maximum tensile stress.

KEYWORDS

Analytical solution, Fourier series technique, Ring test, Stress function, Tensile strength

ARMA 15-0231

Constitutive couplings in unsaturated granular media with crushable grains

Yida Zhang[1], Giuseppe Buscarnera[1]

[1]*Northwestern University*

Crushable granular materials exhibit a complex hydro-mechanical behavior. On one hand, hydraulic variables as relative humidity, suction or degree of saturation alter the crushability of the matrix. On the other one, particle breakage causes major variations of both grain and pore size distributions, impacting the hydraulic properties of a granular soil, such as the permeability and the water retention curve (SWRC).

This paper addresses the continuum modeling of grain crushing in unsaturated sands within the framework of the breakage mechanics theory[2]. This choice will enable us to discuss the effect of the

particle size on both mechanical and hydraulic properties, as well as the interaction between them. First, it will be shown that the decrease of the average grain size during crushing involves a dependency of the SWRC on the current grain size distribution (GSD).[3]. It will be shown that the model prediction can provide a satisfactory agreement when compared with retention curve data obtained for a range of granular soil.
The theory is further applied to simulate the compression response of granular materials at various degrees of saturation, showing that the model can capture a rich set of coupled compression and hydraulic responses. In particular, it is shown that such coupled effect depend on the relative intensity of capillary effects and crushing resistance, generating an intrinsic particle size dependence of the constitutive properties of a granular soil. Physical considerations are provided to elucidate the effect of the grain size on the hydro-mechanical coupling of a granular solid, setting a vision for the future application of this modeling approach also to other classes of geomaterials, such as rockfill and granular rocks.

ARMA 15-0284

Size effect on length and width of fracture process zone

Ali Fakhimi[1], Mehdi Galouei[1]
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A bonded particle model is used to study the fracture process zone (FPZ) in three point bending test of notched beams. Five different beam sizes of 20 (height) × 60 (span), 40 × 120, 80 × 240, 160 × 480, and 320 × 960 mm^2 were tested to investigate the effect of specimen size and material ductility on the length and width of the FPZ at the peak load. For each specimen size, six different random distributions of particles were used; six different realizations were modeled. The material ductility was controlled by using different slopes (different k_{np} values) for the post-peak behavior of contacts between the circular particles in tension. A statistical approach is proposed to more objectively calculate the width and length of the FPZ. The basis of this approach is the distribution of damaged contacts along the width of the FPZ that can be modeled reasonably well by a normal distribution. It is shown that the size of FPZ depends on specimen size and material ductility. In particular, the shape of FPZ is affected by the specimen size. Different regression methods are proposed to be able to calculate the length and width of FPZ and the best linear regression technics is identified and discussed.

ARMA 15-0232

Modelling the shear behaviour of sedimentary rock joints under constant normal stiffness conditions

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The typical shear responses of rock joints have been studied under constant normal load (CNL) or zero normal stiffness condition, but recent studies have shown that this boundary condition may not be replicate more practical situations, and that constant normal stiffness (CNS) is a more appropriate boundary condition to describe the stress-strain response of field joints. In addition to the effect of boundary conditions, the shear responses of a rough joint also depend on its surface properties and initial stress acting on its interface. Despite this, exactly how these parameters affect the shear responses of joints is not fully understood because the stress-strain response of joints is governed by non-uniform asperity damage and the resulting gouge that accumulates on their interfaces. Therefore, an attempt has been made in this study to predict the complete shear responses of rough joints incorporating the asperity deformation under CNS conditions. In order to validate this analytical model, a series of CNS shear tests were conducted on rough tensile (natural) joints and their replicas at a range of initial normal stresses that varied from 0.4 to 1.6 MPa. The comparisons

between the predicted shear responses and experimental results show a close agreement. Finally, the practical applications of this analytical model to typical analysis of jointed rock slope stability and tunnel roof stability are also discussed.

ARMA 15-0157

Numerical Modeling of Rock Brazilian Test: Effects of Test Configuration and Rock Heterogeneity

Sohrab Gheibi[1], Rune M. Holt[1,2], Alexandre Lavrov[2], Diego Mas Ivars[3]

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The Brazilian Test was modeled with FLAC to investigate the effect of loading angle on stress distribution and failure mechanisms in homogeneous and heterogeneous rock samples. The model was first calibrated to data of a Standard Brazilian test of a PMMA sample, found in the literature. Then several numerical Brazilian tests were performed using virtual materials with different deformability. The numerical results indicated that the loading angle (i.e. contact length between the jaw and the disc) is not constant in the Standard Brazilian test and changes depending on the amount of applied load and the deformability of the disc. This means that the contact length will be larger for materials with higher tensile strength and lower Young's modulus. The contact length affects the distribution of both tensile and compressive stresses in the disc. Therefore, it can influence the failure mechanism of the disc. If the contact length is low, probability of shear failure increases close to the loading region, and if it is high, tensile failure is more probable at the center of the disc. Numerical experiments were performed with different values of m=UCS/UTS, where UCS and UTS are Uniaxial Compressive Strength and Uniaxial Tensile Strength, respectively. For two specimens, A and B, with equal tensile strength of 10 MPa but different Young's modulus (of E_A=90 and E_B=5 GPa), the loading angle was 8.5^0 and 18.5^0 for A and B, respectively. Results indicated that in specimen A the failure mechanism was tensile at the center for m>15 and shearing at top of the disc for m<15. For specimen B, it was tensile at the center for m>9 and shearing at the top for m<9.

Furthermore, Uniaxial Tensile (UT), Standard Brazilian (SB) and Brazilian tests with constant loading angle of 30^0 (CLAB) were simulated. Heterogeneities were introduced as inclusions with their tensile strength and Young's modulus randomly selected from a normal distribution with different standard deviations. The analysis indicated that as the standard deviation of the Young's modulus and tensile strength distribution increases, the recorded peak load and peak tensile strength decreases for the three tensile test configurations. However, UT is much more sensitive to the variability of tensile strength than of Young's modulus. In contrast, the SB and CLAB tests indicated more sensitivity to Young's modulus variability.

Keywords: Brazilian test, tensile strength, loading angle, contact length, deformability, heterogeneity

ARMA 15-0575

Micro-scale modeling of the inelastic response of a granular sandstone

Shiva Esna Ashari[1], Giuseppe Buscarnera[1], Gianluca Cusatis[1]

[1]Northwestern University

Granular rocks deformed under laboratory conditions exhibit complex pressure dependent stress–strain responses and strain localization processes. Such class of quasi-brittle materials is in fact characterized by various forms of fine-scale heterogeneity, which generate macroscopic patterns that can be traced back to a range of micro-structural processes, such as crack initiation; crack propagation along complex three-dimensional paths; interaction and coalescence of distributed multi-cracks into localized continuous cracks; and interactions between fractured and unfractured material.

While usual constitutive approaches describing the macro-scale response of porous rocks neglect such rich variety of microscopic processes, discrete numerical models allow the incorporation of material heterogeneity directly at the scale where such processes take place. This paper discusses a

new computational tool for the analysis of inelastic processes in granular rocks subjected to varying levels of confinement. The purpose is to provide a flexible and efficient computational tool for the analysis of failure processes in geomechanical settings.
The proposed model is formulated within the frame of Lattice Discrete Particle Models (LDPM)[1,2], which is calibrated to capture the behavior of a porous rock widely tested in the literature: Bleurswiller sandstone. It is shown that the model allows one to explore the effect of a heterogeneous microstructures on the development of pervasive faulting and strain localization. Most notably, it is discussed how LDPM analyses can be interpreted from a macroscopic perspective, deriving a detailed description of inelastic deformation patterns at the continuum scale. It is further discussed how the combined use of LDPM analyses, continuum modeling, and bifurcation theory can enable one to assess predictive capabilities and limitations of the usual elastoplastic models for sandstones, thus suggesting possible enhancements of their formulation.

Technical Session 36 – Elizabethan CD
Mining Geomechanics

Wednesday, July 1, 2015, 08:00 am - 09:30 am

Chairs: Zach Agioutantis & Arunkumar Rai

ARMA 15-0402

Numerical creep analysis of chalk cavities accounting for joints degradation

Faten Rafeh[1], Hussein Mroueh[1], Sebastien Burlon[2]
[1]LGCgE, Polytech'Lille, Université Lille 1, [2]Université Paris-Est, IFSTTAR
Effect of presence of joints on the failure mechanisms of underground cavities

Nowadays, the fact that huge surfaces are found to be under lied by unexploited cavities constitutes a serious threatening risk of damage on both people and constructions. Hence, a safety analysis providing a risk assessment is recommended in order to control the consequences. This hazardous phenomenon exists in different regions in Europe and is highly concentrated in North France where cavities were excavated in chalk layers by the method of chambers and pillars. Knowing that the chalk layers in this region are originally stratified with joints and discontinuities, an anisotropic behavior is induced and supposed to have a considerable impact on the global response of the excavated cavities. These cavities are required not only to avoid ultimate collapse, but also to satisfy limits of displacement, resistance, and stability. The major intention of this paper is to consider the effect of the anisotropic behavior induced by the presence of joints or weak planes with reduced strength properties embedded in different orientations in the chalk on the behavior of the underground excavation. Induced anisotropy affects the strength and deformability behavior of the chalk continuum and thus influences the strain mechanisms and stability of the excavated structure. To account for this, an oriented yield criterion based on the theory of multi-mechanisms is adopted. In this criterion, general failure is of the intact chalk is first verified, and relevant plastic corrections are applied if needed. The new stresses are then analyzed for failure on the first joint set, and updated accordingly. By iteration, the model allows to pass from one joint set to the other to reach the values of stresses and deformations equivalent to the rock body embedded with joint sets by which these stresses do not surpass the superposition of the yield surfaces corresponding to each of the intact chalk and the weak planes. This criterion is incorporated in the numerical technique developed to study the stability state of these cavities. Since in shallow excavations dominating failure is often realized by shear, the approach developed is based on the conventional shear strength reduction method. Numerical models of underground structures exploited by chambers and pillars are implemented. The effect of joint sets orientation and number on the shear strength reduction factor as well as on the strain profiles is illustrated and analyzed. This study illustrates the influence of induced anisotropy on the stability and failure mechanisms of the underground excavations.

ARMA 15-0488

Investigation the Effect of Cyclic Loading on Fracture Propagation in Rocks by Using Computed Tomography (CT) Techniques

Morteza Ghamgosar[1], Nazife Erarslan[1]
[1]The Univerity of Queensland

Tensile strength of brittle rocks is one the most significant parameters influencing rock fracturing and propagation of micro fractures in rock crushing, blasting and cutting. The Brazilian test is the most common and simple method used to determine the indirect tensile strength of rocks. In Brazilian test, applied diametrical compression stress induces indirect tensile stresses normal to the vertical plane crossing through the rock disc, and the ultimate failure occurred at the place where the maximum tensile stress is concentrated. However, rocks have discontinuities as they are heterogeneous materials, the mechanical behaviour of rock with those pre-exiting heterogeneities (pre-existing cracks) under static loading have been studied widely. In this study, the specifications of Brisbane Tuff Cracked Chevron Notched Brazilian Disc (CCNBD) sample geometry have been selected according to the suggestions of International Society of Rock Mechanics (ISRM). To investigate the fracturing behaviour of rocks under static and cyclic loading by using X-ray Computed Tomography (CT) techniques. The fracturing behaviour of rocks technically depends on the nature of loading, strength of mineral and text of rocks. Laboratory observations demonstrated that there is a distinct difference in fracturing between the static and cyclic loading. However, the initiation of fracturing is the main concern in many fracturing researches. Especially, the behaviour of Fracture Process Zone (FPZ) depending on the various loading types is still unknown in literature. That's why; the Computed Tomography (CT) scan's results demonstrated in this research. The loading waveform at the tip of chevron notch pre-existing crack in CCNBD specimen caused the damage in rock by the occurrence of FPZ.

It was found that the cyclic loading had an important effect on micro-fracture propagation through the FPZ zone. Moreover, laboratory results confirmed that increasing amplitude and frequencies with cyclic loading decreased the stress-energy released in the rock specimen.

Keyword
Computed Tomography (CT), Fracture Process Zone (FPZ), Roc Micro-fracture Propagation

ARMA 15-0623

Relationship Between Compressive Strength and Index Properties of Rock

Bibhuti Panda[1], Srikant Annavarapu[1]
[1]Amec Foster Wheeler

The uniaxial compressive strength data is used in the mine design to develop input parameters for rock mass classification. The purpose of this study is to develop a correlation between the compressive strength and other index tests for various rock units for a proposed mine. The various index tests were performed to develop the compressive strength value to be used in the design of the mine during prefeasibility-level study. The point load tests (PLT), Schmidt Hammer tests (SHT) and density tests were also performed along with uniaxial compressive strength tests (UCS) in order to develop a correlation among the compressive strength and index tests. About 700 point load tests, 155 Schimdt Hammer tests and 70 uniaxial compressive strength tests for rock cores retrieved from the investigation site were performed. The SHT and density tests were performed for all rock cores that were tested for UCS. It was not possible to test the PLT and UCS using the same rock core sample. The PLT tests were performed using both dimetral and axial test methods. The point load test data was broadly classified into two categories based on the failure surface. The intact failure strength represented the failure plane through intact rock while structural failure strength represented failure through preexisting bedding, fracture or joint plane.

The rock groups at the site was broadly classified into three (3) rock group category (A-Limestone, B-Weak rocks and C- Breccia) based on point load strength. Only intact failure point load strength data was used to find the relation between PLT and UCS. The point load strength for Breccias was the highest while the same for Weak rocks was the lowest. The mean PLT Is (50) values for three major rock categories Limestone, Weak Rocks and Breccias was 521 psi (pounds per square inch), 232 psi and 1334 psi respectively. The mean rebound number values for three major rock categories Limestone, Weak Rocks and Breccias was 58, 50 and 60 respectively. The relationship between PLT and UCS was established by comparing the mean strength value for each rock group. There is a good relationship found between compressive strength and point load index for Limestone rock group. The ratio of mean UCS to mean PLT for this rock group is 24. This ratio has been presented in the literature for many rock groups. On the other hand the UCS/PLT ratio was found to be 16 for Weak rock and 10 for Breccias. The point load strength from dimetral tests was found to be lower than axial tests. A good relationship is also found between density and UCS. This relationship is nonlinear and is better represented for Breccias. The relation between hammer test and UCS is found to be nonlinear for all rock groups. The correlation between UCS and SHT was not very good.

ARMA 15-0807

Correlation of the Rock Mass Rating System (RMR) to the Unified Soil Classification System (USCS) for Geotechnical characterization of Very Weak Rock Masses

Sean Warren[1], Raj Kallu[1], Chase Barnard[1]
[1] *Univ of Nevada-Reno*

Underground gold mines in Nevada are typically hosted in weak to very weak rock masses making standard rock mass classification systems insensitive to variations in rock quality. The Rock Mass Rating (RMR) classification system is widely used at underground gold mines in Nevada and is applicable in good to fair quality rock but is difficult to apply and loses reliability in weak and, especially, very weak rock masses. Because of the weak rock types encountered in these mines, we propose a modified calculation of RMR to increase sensitivity in weak rocks (W-RMR), in addition to the use of the Unified Soil classification (USCS) for geotechnical classification and material property estimation.

An evaluation of the RMR and W-RMR classification systems was completed through analyses of geotechnical mapping data conducted at four underground gold mines in Nevada. Statistical analyses of field data indicates that the W-RMR system is more sensitive in the weak rock range (W-RMR <40) and is well correlated to RMR in fair to good quality rock. The use of both soil and rock classification systems in weak rock makes a correlation between them useful for numerical computation and comparative purposes. A correlation between the W-RMR and USCS systems was developed by comparing geotechnical W-RMR mapping to laboratory testing of bulk samples.

ARMA 15-0464

Discrete Modeling of Multiple Discontinuities in Rock Mass using XFEM

Kamal Das[1], R Ausas[2], Ignacio Carol[3], Eduardo Rocha Rodrigues [4], Sandeep S. Sandha[1], Pablo E. Vargas[5], Nubia A. González[5], J.M. Segura Serra[6], M.R. Lakshmikantha[6], Ulisses Mello[4]
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Modeling of discontinuities (fractures and fault surfaces) is of major importance to assess the geo-mechanical behavior of oil and gas reservoirs, especially for tight and unconventional reservoirs. Numerical analysis of discrete discontinuities traditionally has been studied using interface element concepts, however more recently there are attempts to use extended finite element method (XFEM). The development of an XFEM tool for geo-mechanical fractures/faults modeling has significant industrial potential; particularly within the hydrocarbon industry where it could lead to improved predictions for porosity/permeability changes in coupled geomechanical reservoirs. In this paper, we present a novel methodology based on the extended finite element method (XFEM) to analyze the

behavior of pre-existing multiple strong discontinuities (faults and/or fractures) in reservoir rock. Detailed mathematical framework leveraging XFEM for multiple discontinuities in rock masses has been derived. This XFEM based framework is robust enough to represent strong discontinuities independently of the mesh. The approximation of discontinuities is constructed in terms of Heaviside functions and junction functions which lead to additional unknowns to capture the displacement jump across and at intersections of joints. The method has been improved to include Neumann and Dirichlet boundary conditions applied in the enriched part of the domain. Our framework and algorithm are general in nature and can handle complex geo-mechanical problems with different loading conditions.

For validation of the implemented mathematical framework using XFEM, we analyze the behavior of a rock sample with multiple discontinuities under different loading conditions and compare displacement and stress with known theoretical solution. Triaxial3D loading examples involving multiple discontinuities are also presented to demonstrate the accuracy and robustness of the proposed methodology.

Technical Session 37 – California West
Wellbore & Drilling Mechanics 2

Wednesday, July 1, 2015, 11:00 am - 12:30 pm

Chairs: Rick Chalaturnyk & Paul Hagin

ARMA 15-0349

A framework for wellbore cement integrity analysis

Gerd-Jan Schreppers[1]
[1] *TNO DIANA BV*

Steel casings are cemented in wellbores to ensure that the production of oil and gas can be controlled during the operation of the well and at the well-bore end of life. The sealing properties of the cement are essential in this respect. Loading history during construction and operation of the well and long-term material behavior characteristics may affect the integrity of the cement and its sealing capacity. Several failure potential modes are identified: cracking of cement, shear failure of cement, de-bonding of cement and casing and de-bonding of cement and rock. In this paper a nonlinear staggered heat-transfer-stress analysis for both 2-dimensional and 3-dimensional models is presented. The analysis simulates and evaluates the sealing properties of the cement and calculates the chance that one or more of the failure modes occurs. In the analysis both the construction phases of the well and typical loadings during operation, such as over-pressures and temperature changes, are considered. Rock is modelled with an elasto-plastic Mohr-Coulomb material model. Cement is defined with a multi-directional fixed crack model for tension failure combined with a Mohr-Coulomb elastic-plastic model for shear-failure. For the steel casing a von Mises elasto-plastic material model is assumed. De-bonding elements are applied between casing and cement and between cement and rock. Creep and shrinkage of cement can be considered as an option. The model is parameterized so-that variations in material properties and loadings can be easily made and the effect of these variations on the sealing properties of the cement can be easily assessed. These analyses will support the well-engineer in checking the sealing properties of different cements for a well.

ARMA 15-0110

Numerical study of thermal stresses in casing-cement-rock system with heterogeneity

Alexandre Lavrov[1], Jelena Todorovic[1], Malin Torsater[1]
[1] *SINTEF Petroleum Research*

Access to hydrocarbon reserves is commonly obtained by means of cased and cemented wells. Integrity of the near-well region is of utmost importance for preventing leakage between geological strata and towards the surface. This includes integrity of the cement column, the adjacent rock, and the casing-cement and cement-rock interfaces. Thermal cycling caused by injection of relatively cold or warm fluids into the well, or by production of reservoir fluids, creates thermal stresses in the casing-cement-rock (CCR) system that may result in debonding or radial tensile fracturing [*Lavrov et al.*, 2014]. This may jeopardize the integrity in the near-well area, with eventual leakage as a result.
The quality of cement set in the annulus under real downhole conditions is often far from perfect, and the cement sheath may contain voids. Imperfect displacement of the fluid that was present in the annulus, by cement moving upwards, may create imperfections along the interfaces between cement and casing, and cement and rock. In this study, we demonstrate how heterogeneities present in cement can affect thermal stresses induced during thermal cycling of the CCR system. Finite-element analysis is used to study the build-up of tensile stresses and induced damage in cement. It is shown that contrast in thermal conductivity between damaged cement (voids) and intact cement is a significant contributor to the development of tensile stresses during thermal cycling. On the other hand, contrast in the Young's modulus, the damaged material being softer than the intact one, has lesser effect.
The results allow us to identify the most significant controlling parameters in numerical modelling of CCR systems subject to thermal cycling. Since properties of damaged materials represent a major uncertainty in CCR modelling, the results are highly relevant for reducing the extent of the parametric space in modelling campaigns. They also provide a new insight into the physics of damage development during thermal cycling of casing-cement-rock assemblies.

ARMA 15-0118

Wellbore Stress Changes and Microannulus Development Because of Cement Shrinkage

Mohammad Oyarhossein[1], Maurice B Dusseault[1]
[1] *University of Waterloo*

The integrity of an energy wellbore should be sustained for its entire active life and for a lengthy period thereafter. This means that all relevant short- and long-term parameters that could affect wellbore integrity in the long-term should be taken into account when designing primary completions. Further, this implies that best operational procedures should be followed in drilling, completion and production phases so that the probability of sustained wellbore integrity is very high.
Given good quality drilling, primary cementing quality is a keystone of wellbore integrity. This requires assessment of the effect of density and additives on cement behavior during placement, set, curing and well performance. The goal is always to reduce future problems related to fluid migration between zones, and also to eliminate or reduce the probability of gas migration behind casing toward the surface and the shallow aquifer systems.
We assess the effects of stress changes during and after the primary cementing operation using 2D models considering elastic formation response and varying amounts of cement shrinkage. Cement shrinkage arising from various sources results in a lowering of near-wellbore radial stress as the shrinkage develops. In stiff strata, the inward radial movement of the rock as the radial stress is reduced is small, so the stress path can lead to the condition where the formation pore pressure exceeds the radial total stress, $\sigma_r < p_o$, which is the condition for hydraulic fracturing. The same process can develop as the result of drilling mudcake desiccation after cement placement, and this condition is more likely encountered in cases of extensive borehole breakouts or washouts, as the

hole cleaning procedures may be incompletely effective in removing mudcake. We also note that in the case of thermal wells (steam injection or hot fluid production), thermal dehydration and consequent shrinkage of formation shales can severely constrain the possibility of achieving a permanent seal.

If a microannular space develops as the result of these processes, a vertically continuous pathway can develop. If this vertical path becomes filled with gas, a self-driving fracture can be generated that makes it easier for the hydraulic fracture condition to be reached as the height of the fluid column increases. This can lead to microannular space opening more easily as the height of the continuous vertical pathway increases. A pathway may not develop immediately after primary cementation and set because the continuous fluid column can be slow to develop, leading to gas migration even after the wellbore is abandoned according to regulations. Further, there are sound physical arguments and field evidence that the gas migration under these conditions is pulsed in nature because when gas breakthrough occurs, pressure relief can lead to temporary reclosure of the microannulus.

We present sensitivity analysis of these mechanisms, including differential far-field stresses, and their effects on the possible development of vertical fractures, using realistic values of rock properties and shrinkage.

ARMA 15-0301

Impact of Depletion on Integrity of Sand Screen in Depleted Unconsolidated Sandstone Formation

Yanhui Han[1], Andrew Tallin[1], George Wong[2]
[1]Shell Intl E & P, [2]Shell E & P

Open hole standalone screens and gravel packs are two often-used sand control methods in unconsolidated sandstone. As reservoir pressure depletes, the effective stresses in the formation increase. Due to the stress concentration effect, the depletion induced increase of maximum effective stress around wellbore is further magnified. Because the strength of unconsolidated sandstone is low and the gravel pack usually can only provide very limited support to the wellbore wall, plastic deformation near the well seems inevitable in many wells. As a result, the forces acting on the sand screen increase. When formation loads exceed the loading capacity of the sand screen, the integrity of the screen is lost resulting in sand control failure and in many cases loss of production.

In this paper, the integrity of sand screen is evaluated for various depletions using fluid-mechanical coupling analysis. The interaction between the screen and reservoir is captured by rock-structure interaction model, based on laboratory tests that measured the mechanical properties of ceramic proppant, the formation sandstone and of several sand screens.

The frictional hardening properties of the ceramic proppant and sandstone core plugs are measured by performing constant mean-stress tests in rock mechanics laboratory. The volumetric hardening curve of sandstone is measured in isotropic compression tests (with unloading excursions). The elasto-plastic mechanical properties of sand screen are determined by calibrating the laboratory crushing test data.

For a given maximum depletion, this model can be used to select appropriate sand screens; conversely, for a given sand screen, this model can be used to estimate the depletion where failure is likely.

ARMA 15-0287

Stick-slip instabilities in rotary drilling systems

Alexandre Duepohon[1,2], Emmanuel Detournay[2]
[1]Strutural and Stochastic Dynamics, ArGEnCo, Université de Liège, [2]Department of Civil, Environmental and Geo- Engineering, University of Minnesota

Rotary drilling systems are known to experience instability regimes of various nature, *e.g.*, bit bouncing or bit whirling, that are detrimental to the drilling performance and tool life. In this paper, we focus on another type of instability: stick-slip oscillations. In particular, we revisit the stability analysis of the discrete model proposed by Richard et al. to study the self-excited torsional and axial vibrations of deep drilling systems.

Specific to the model is the definition of the drilling action as the sum of two components, one representing fragmentation and excavation of rocks by the bit cutters, the other a frictional contact process taking place on the cutter wearflats. As a direct consequence of the bit rotary motion, the account of the cutting process, which is a function of the height of the rock ridge in front of the cutters, introduces a so-called regenerative effect in the model governing equations that are therefore of the retarded differential equation type with a discrete state-dependent delay.

A linear stability analysis, which includes the dynamics of the state-dependent delay, reveals that the steady-state motion of the model is unstable, for all parametric configurations; a result that is in contradiction with previous analyses that neglect the delay dynamics. Further investigations show, however, that instability growth can occur either on a slow or a fast timescale as compared to that associated with the resonant period of the model. For fast configurations, the steady-state solution rapidly degenerates into stick-slip oscillations or a bit bouncing instability, in the presence of external perturbations. For slow configurations, the evolution of the instability is so slow that the system behaves like a marginally stable one, which justifies the apparent co-existence of stable regimes when considering the bit dynamics on the timescale of its motion. Interestingly, the boundary between the two regimes corresponds to a critical imposed rotation speed Ω_c, with fast (slow) configurations corresponding to $\Omega_0 < \Omega_c$ ($\Omega_0 < \Omega_c$). This suggests that increasing the imposed rotation speed Ω_0 can contribute to reducing the occurrence of stick-slip, which concurs with observations.

The main step for assessing the stability of the model steady-state while including the dynamics of the delay are presented in the paper. They are followed by the application of the theory to a reference configuration corresponding to a deep drilling situation. Detailed results are presented to illustrate the different behaviors expected above and below the critical speed Ω_c.

ARMA 15-0005

Three Dimension Geomechanical Modeling for Drilling In Caronate Reservoirs

Taoufik Ait-Ettajer[1], LAKSHMIKANTHA MOOKANAHALLIPATNA RAMASESHA[1], Laurent Fontanelli[1]

[1]*Respol U.S.A.*

The three dimensional modeling of geomechanical properties is an important during the drilling process of the wells in carbonate reservoirs. An inadequate calibration of key parameters might increase the cost of the drilling and/or cause damages to the reservoir. Some of the key parameters, such as mud weight and injection pressure, are related to the geomechanical properties of the layers traversed by the well during the drilling process, and throughout the life of the well. Classical approaches tend to build a one dimension geomechanical model (*1DMEM*) along the well. This technique is becoming inadequate with the increase of the number of horizontal wells. The drilling and development of those types of wells require a precise geomechanical model in three dimensions, as the well might cross rocks of different rock strengths in the horizontal and vertical directions. This requirement becomes more essential in the case of carbonates reservoirs with heterogeneous rock strengths distribution. The Poisson Ratio (ν) is one of the most important geomechanical parameters used during the drilling process, since it is related to the Fracture Parting Pressure (*FPP*) using the following equation:

With Z is the depth below sea level, G_{ob} is the overburden gradient and G_r the reservoir pressure gradient.

Previous studies showed that ν can be inferred from lithological parameters, such as facies, *or* geophysical parameters such as velocity. The advantage of the velocity volume, commonly used by

the geophysicists, is the possibility to assess the horizontal and vertical value of the velocity. However, the vertical resolution of the velocity volume, which is often more than 20 feet, is not adapted to the required drilling resolution which is in the range of few feet.
In this paper, we propose a stochastic approach that will allow the three dimension modeling, at a foot resolution, of the Poisson Ration, prior to the calculation of the FPP at each location of the reservoir. This workflow reconciles, in geostatistical way, the laboratory data, the well log data, such sonic logs and the geostatistical parameters.

Technical Session 38 – California East
CO_2 Sequestration - Experiments and Modeling

Wednesday, July 1, 2015, 11:00 am - 12:30 pm

Chair: TBD

ARMA 15-0290

Geomechanical Modeling to Predict Wellbore Stresses and Strains for the Design of Wellbore Seal Repair Materials for Use at a CO_2 Injection Site

Steven Sobolik[1], Steven Gomez[2], Edward Matteo[1], Thomas Dewers[1], Pania Newell[1], John Stormont[2], Mahmoud Taha[2]
[1]Sandia National Laboratories, [2]University of New Mexico

This paper will present the results of large-scale three-dimensional calculations simulating the hydrological-mechanical behavior of a CO_2 injection reservoir and the resulting effects on wellbore casings and sealant repair materials. A critical aspect of designing effective wellbore seal repair materials is predicting thermo-mechanical perturbations in local stress that can compromise seal integrity. The DOE-NETL project "Wellbore Seal Repair Using Nanocomposite Materials," is interested in the stress-strain history of abandoned wells, as well as changes in local pressure, stress, and temperature conditions that accompany carbon dioxide injection or brine extraction.

Three distinct computational models comprise the current modeling effort. The first is a field scale model that uses the stratigraphy, material properties, and injection history from a pilot CO_2 injection operation in Cranfield, MS to develop a stress-strain history for wellbore locations from 100 to 400 meters from an injection well. The results from the field scale model are used as input to a more detailed model of a wellbore casing. The 3D wellbore model examines the impacts of various loading scenarios on a casing structure. This model has been developed in conjunction with bench-top experiments of an integrated seal system in an idealized scaled wellbore mock-up being used to test candidate seal repair materials. The third computational model depicts bench-top experimentation and will be used to gain an understanding of the wellbore microannulus compressibility and permeability. The results from these models will be used to estimate the necessary mechanical properties needed for a successful repair material.

This material is based in part upon work supported by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) under Grant Number DE-FE0009562. This project is managed and administered by the Storage Division of the NETL and funded by DOE/NETL and cost-sharing partners. This work was also funded in part by the Center for Frontiers of Subsurface Energy Security, an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences under Award DE-SC-0001114.

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ARMA 15-0569

MULTIPHASE FLOW IN FRACTURED POROUS MEDIA: APPLICATION TO CO2 LEAKAGES FROM NATURAL AND STIMULATED FRACTURES

Souheil Ezzedine[1]
[1]*LLNL*

Leakage to the atmosphere of a significant fraction of injected CO2 would constitute a failure of a geological CO2 storage project from a greenhouse gas mitigation perspective. We present a numerical model that simulates flow and transport of CO2 into heterogeneous subsurface systems. The model, StoTran, is a flexible numerical environment that uses state-of-the-art finite element and finite volume methods and unstructured adaptive mesh refinement scheme implemented using MPI and OpenMP protocols. Multiphase flow equations and the geomechanical equations are implicitly solved and either fully or sequentially coupled. StoTran can address inverse and forward problems under deterministic or stochastic conditions. For the current study, StoTran has been used to simulate several scenarios spanning from a homogeneous single layered reservoir to heterogeneous multi-layered systems, which including cap-rock with embedded fractures, have been simulated under different operations of CO2 injection and CO2 leakages conditions. Results show the impact of the injection and leakage rates on the time evolution of the spread of the CO2 plume, its interception of the fractured cap-rock and the risk associated with the contamination of the overlaying aquifer. Spatial and temporal moments have been calculated for different, deterministic of stochastic, subsurface physical and chemical properties. Spatial moments enable assessing the extent of the region of investigation under conditions of uncertainty. Furthermore, several leakage scenarios show the intermittence behavior and development of the CO2 plume in the subsurface; its first interception with the fractures located further far from the injection well then, at a second stage, its interception with the fracture within the immediate vicinity of the injection well. We will present a remedy to CO2 leakages from the reservoir in order to enhance a long term containment of the injected CO2.

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ARMA 15-0127

Geomechanical evaluation of fault reactivation potential and uplift at the South West Hub geological CO_2 storage site, Western Australia

Yanhua Zhang[1], Laurent Langhi Langhi[1], Claudio Delle Piane[1], Peter Schaubs[1], Dave Dewhurst[1], Linda Stalker[1], Karsten Michael[1]
[1]*CSIRO*

An area in the Southern Perth Basin has been identified as a potentially suitable site for CO_2 injection, due to its proximity to major CO_2 emission sources and the presence of potentially suitable geology. The project for testing and proving up of the storage area is known as the South West Hub Project or SW Hub. Recently acquired 2D seismic and well data have allowed a detailed description of facies, measurement of rock properties and development of a 3D structural model for the area. This 3D model has been used as the basis for a preliminary fault seal analysis and also for the development of simplified geomechanical models for the SW Hub using FLAC3D. While there is

still uncertainty regarding the subsurface geology, the preliminary fault seal analysis identified a few potential areas of cross fault flow at reservoir level, although no up fault flow was envisaged. The geomechanical modelling used in situ stress (magnitude, orientation) and pore pressure conditions as a starting point and then simulated CO_2 injection from a single well at rates of 1 to 5 million tons per year for 20 years. In the models, the geomechanical and hydrological properties for the target injection reservoir and the barrier/baffle characteristics of overlying stratigraphic units are based on experimental data from drill core samples from the Harvey-1 well. The data for other rock units in the stratigraphic sequences of the model were chosen based on rock types, information from the literature and new experimental data. Different scenarios were tested involving weak faults and strong faults. Cross-fault permeability was set at reservoir rock permeability for sand-sand contacts and for shale permeability at sand-shale contacts. No matter whether weak or strong faults were used, no faults were reactivated nor the top seal breached under any of the simulated injection rates. Average uplift in the weak fault scenario was modelled at between 0.4 and 1.8 cm for injection rates of 1 to 5 million tons per year. The strong fault model showed slightly smaller uplifts. The majority of uplift was noted in the first 5 years of injection and flattened off rapidly after this point in time. This is consistent with geomechanical models from other CO_2 storage sites and from actual field measurements. The high flow velocities caused by injection are localized immediately around the injection site, with rapid velocity decrease away from the site. Modelled flow patterns suggest that ground waters would be displaced laterally in the reservoir horizon, with flow velocity vectors divergent from the injection site. However, flow velocities in far-field areas and in the stratigraphic horizons above the reservoir sandstone are very small or negligible. There is no modelled upward flow discharge along the faults and limited (< 1 MPa) pore pressure increase. It should be stressed that these models are preliminary and that revisions will be likely after the acquisition of 3D seismic data which will refine the subsurface model and the drilling of new wells which will firm up rock and subsurface fluid flow properties.

ARMA 15-0165
A coupled geochemical-transport-geomechanical model to address caprock integrity during long-term CO_2 storage

Ellen F. van der Veer[1], Svenja Waldmann[1], Peter A. Fokker[1]
[1] *TNO*

The success of CO_2 storage projects is threatened, amongst others, by leakage of faults through the caprock. The injection of CO_2 into a reservoir is accompanied by changes in pressure, temperature, and chemical composition of the formation water and mineral assemblage. When CO_2 is entering a fault in the caprock, and gets dissolved in the formation water, chemical processes may change the porosity and permeability of the fault. Also, changing pressures may induce stress changes and faults may be reactivated. Both processes thus change the flow properties. We set up a coupled geochemical-transport-geomechanical model to assess the coupled effect of these processes on the leakage risk during long term CO_2 storage. We coupled the geochemical modeling code PHREEQC to the flow module MRST, the Matlab Reservoir Simulation Tool. Pressure changes along a clay fault were updated for changes in chemistry and flow. The resulting pressure distribution was used with poroelastic coupling to determine the effect on the subsurface stresses and the associated potential for fault reactivation. For the latter, we used a basic slip tendency analysis. Where possible, we included results of permeability and friction experiments into our model set-up.

The potential for fault reactivation was mainly dependent on porosity changes. We found that for the injection of pure CO_2, porosity changes were very small and no significant fault reactivation could be expected. Introduction of impurities (e.g. SO_2) into the CO_2, however, led to significant porosity changes and corresponding pressure changes along the fault, which led to fault reactivation if the pressure build-up was large enough.

Changes in chemical composition can occur when CO_2 resides in a reservoir for very long time scales. Injection of impure CO_2 may so on the long term lead to significant porosity changes in clay faults and therefore to pressure build up and potential fault reactivation.

ARMA 15-0384

Dynamic rupture modeling of injection-induced seismicity: Influence of pressure diffusion below porous aquifers

Loes Buijze[1], Bogdan Orlic[1], Brecht Wassing[1], Gerd-Jan Schreppers[2]
[1]TNO, [2]TNO DIANA

Studying production- and injection-induced fault reactivation and induced seismicity is important in the context of CO2 storage, as it may affect the sealing integrity of the reservoir or the storage site, cause damage to surface infrastructure and raise concern amongst the local population.
Past studies often use a Mohr-Coulomb friction constitutive relation, with or without strain softening, to model the process of fault reactivation. The dynamic effects of fault rupture are typically neglected, although they are important, for example to study the magnitude of slip and the seismic waves generated during seismic event. From laboratory experiments it is known that the friction is not constant but evolves as a function of slip distance and slip rate, which is described by the empirically derived rate-and-state friction (RSF) laws. The RSF-formulations provide a more realistic description of the fault failure and rupture behavior and also of the pre- and post-failure behavior, which is important to capture the dynamic effects of seismic events.
In this research, we implemented rate-and-state friction as a constitutive model for interface elements in the finite element software package DIANA to better model the dynamic frictional behavior and seismic characteristics during fault reactivation. We briefly explain the rate-and-state theory and present verification of our FE implementation. We also show the potential for application of RSF laws in field-scale geomechanical models of fault reactivation due to pressure changes. Fully dynamic runs on generic 2D models, using a set up relevant for CO2 storage sites, are presented and compared to the runs with the classical Mohr-Coulomb friction for faults.

ARMA 15-0399

Numerical study of the impact of CO_2-fluid-rock interactions on porosity and permeability evolution in fractured carbonate rocks

Yue Hao[1], Megan Smith[1], Harris Mason[1], Susan Carroll[1]
[1]Lawrence Livermore National Laboratory

One of the primary research areas for CO_2 sequestration/enhanced oil recovery (EOR) operations is to develop a good understanding of CO_2-fluid-rock interactions and assess their effects on rock porosity and permeability evolution, which may alter the performance or behavior of reservoir systems. To this purpose, there is a need to develop reliable reactive transport models, which are able to accurately represent essential features of CO_2-fluid-rock interactions at both laboratory and field scales. An important challenge in modeling reactive transport and mineral chemical alteration processes, particularly in a heterogeneous and fractured rock system, is the identification of effective macroscopic parameters (e.g. chemical rate kinetics, porosity-permeability relationships, reactive surface area correlations) required by the continuum-scale (macroscopic scale) models. A lack of proper calibration or upscaling of these effective property parameters would inevitably lead to great uncertainty in model predictions. In this study we used CO_2 core-flood experimental data to develop and calibrate a three-dimensional continuum-scale reactive transport model for simulating CO_2-induced rock porosity and permeability evolution. During the core flooding experiments the CO_2-equilibrated brine was injected into carbonate rock samples, which were collected from the Arbuckle carbonate reservoir, Wellington, Kansas. We analyzed X-ray computed microtomography (XCMT) characterization data to examine heterogeneous distributions of pore structures, naturally occurring fractures, and mineral phases inside the cores, and then used them to constrain initial model macroscopic properties including porosity, permeability, and mineral compositions. Model chemical kinetic, porosity-permeability, and porosity-surface area correlations were also calibrated with the experimental measurements. The reactive transport simulations were performed by the Nonisothermal Unsaturated Flow and Transport (NUFT) code, and their results are compared with experimental data. Both experimental and numerical results show that natural fractures, which were connected with pre-existing macro pore spaces to form main preferential flow pathways in the core, largely controlled the distribution of injected fluid, carbonate dissolution, and consequently porosity and permeability evolution. As fracture apertures further increased with mineral dissolution fluid concentration gradients started to develop between the fracture center and wall, and carbonate dissolution became limited by mass transfer, therefore resulting in a reduced pH buffering capacity of the rock core. Our model results indicate that the calibrated continuum-scale reactive transport models are able to adequately predict the dissolution behavior of fractured carbonate rocks at a core scale. In addition the model calibration against core flood experiments provides a useful basis for upscaling reactive transport properties used to describe carbonate dissolution from the laboratory (core) scale to field (reservoir) scale. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Technical Session 39 – Elizabethan AB
Hazard Prediction and Mitigation
Wednesday, July 1, 2015, 11:00 am - 12:30 pm
Chairs: Florian Amann & Keh-Jian Shou

ARMA 15-0180

Remote Structural Mapping and Discrete Fracture Networks to Calculate Rock Fall Volumes at Tornado Mountain, British Columbia

Renato Macciotta[1], C. Derek Martin[1]
[1]*University of Alberta*

Design of rock fall protection structures requires information about the trajectory of the rock blocks and their volume. Rock fall spatial distribution and heights are direct input for the dimensioning of these structures, and block velocities and volumes (therefore their masses) are used to calculate the impact energies to be supported. Rock fall velocities are typically calculated using trajectory models calibrated against previous rock fall occurrences. Rock fall volumes can be calculated from previous events if records are available, or from estimations of block sizes at the rock fall sources. The frequency distributions of rock fall velocities and volumes are combined to calculate the distribution of impact energies at any given location, which is the basis for a reliability-based design of the protection structures.

A 110m-long lock-block wall was built to protect a section of railway track in Tornado Mountain, British Columbia, following a 2.2m-diamter rock fall that crossed the railway alignment. Site investigations provided detail information of the rock fall trajectory and source location. The work presented here illustrates the use of photogrammetry to obtain structural information at the rock fall source and use it to calculate the volumes of blocks travelling downslope and reaching the protection structure. The 3-dimensional elevation model obtained by the photogrammetric technique is used to measure visible block sizes and estimate their volumes. The distribution of joint spacings measured in the 3-dimensional model is then used together with a random sampling technique to calculate a distribution of block volumes within the rock mass. Finally, structure orientation and spacing are used to build a discrete fracture network (DFN) and calculate the distribution of volumes of the intact blocks within the network. The block volume distributions calculated with the three approaches are compared against rock fall volumes surveyed along the rock fall path. The agreement between the surveyed volumes and the distribution calculated with the DFN suggests that assuming persistent fractures within a DFN can be used to estimate rock fall volume distributions. Considering persistent fractures within the DFN appears to be a simple approach to account for the rock mass disaggregation necessary for block detachment and the disaggregation occurring while travelling downslope

ARMA 15-0419

Understanding the Correlation between Induced Seismicity and Wastewater Injection in the Fort Worth Basin

Valerie Gono[1], Jon Olson[1], Julia Gale[1]

[1]*The University of Texas at Austin*

Since 2010, there has been an increase in the cumulative number of earthquakes that occurred in the United States.[4] This can be attributed to the rapid expansion of shale development through hydraulic fracturing, which resulted in large volume disposals of wastewater through injection into the formation. Extensive studies have been done regarding the correlation between injection wells and induced seismicity. However, there still isn't a model that can accurately simulate the correlation between induced seismicity and fluid injection.

In this study, a reservoir simulation was performed using the Computer Modeling Group (CMG) Implicit Explicit Black Oil (IMEX) simulator for all the Fort Worth Basin (FWB) injection wells with available relevant data. These data include the minimum and maximum injection depths, the monthly injection volumes, and the monthly injection pressures. One of the challenges in assessing fluid pressure changes that might induce seismicity on a basin-wide scale is the high uncertainty associated with the geological inputs (primarily permeability thickness). Using a Cartesian coordinate system, the current model has 342 cells in the x-direction, 330 cells in the y-direction, and is divided into 9 different layers in the z-direction. The total area of interest is approximately 130 miles by 125 miles. Addition of flow barriers, such as faults, can cause regional and local pressure distribution heterogeneities. The simulation results show that where earthquakes have occurred, there is some spatial and temporal correlation with injection well locations and substantial predicted increases in pore pressure. However, not all areas with high numbers of injection wells and elevated pore pressures are correlated with seismic activity.

Fault slip can be triggered by changes in the effective stress state due to subsurface fluid injection or extraction, but to generate earthquake events that can be recorded by standard seismic arrays or felt by people at the surface, fairly large pre-existing faults are required. The apparent correlation of induced quake size with depth suggests that the available shear stress to be released may also influence event likelihood. Finally, injection at greater depth increases the likelihood of pressurization of low permeability basement, where flow can be localized along large-scale faults. A lack of any of these conditions may explain the lack of correlation between some regions of increased pore pressure and induced seismicity.

ARMA 15-0792

Stability of the rock block system that initiated the Jiweishan landslide in China

Pinnaduwa Kulatilake[1]

[1]*University of Arizona*

The objective of the paper is to investigate the initiation of the Jiweishan landslide by simulating the field geological conditions around and inside a selected rock block system and then to study its stability through 3-D discontinuum stress analyses. The scope was limited to investigating only the possible detachment of the whole block or parts of the block from the top of the mountain. No attempt was made to simulate falling trajectories of the blocks or debris flow associated with the landslide. A methodology is introduced in the paper to apply realistic boundary conditions to the rock mass and to facilitate simulation of topography and stratigraphy that existed prior to the landslide. The following conclusions can be drawn from the performed 3-D discontinuum numerical stress analysis: (1) It showed clearly that the gravitational loading and the mining excavations that occurred underneath the investigated block at the landslide site played very important roles with respect to the instability of the investigated block (see Fig. 1); (2) It indicated that the northern part of the investigated block (key block) had moved along the strike of the north boundary discontinuity plane (T2) and had undergone shear failure on the T2 surface as well as on a weak shale layer (the sliding plane) and the remaining part of the investigated block (driving block) had undergone shear failure on the sliding plane and separation from southern and western boundary discontinuity planes (T0 and T1) to fill the empty space created by the key block to initiate the Jiweishan landslide; (3) It indicated that the key block had moved out first from the top of the mountain in a direction parallel to the strike of T2 discontinuity and then the driving block had moved out from the mountain along a direction slightly east of the north direction to initiate the landslide; (4) It showed that it was necessary for the effective friction angle of T2 discontinuities and sliding plane to drop to a value less than 10^0 to have instability of the investigated block. This means that the rainfall and karstification have played major roles in reducing the said effective friction angle and contributing to the failure of the investigated block; (5) It showed that the dip angle of the sliding plane and the effective friction angle of T2 discontinuities and the sliding plane have played very important roles with respect to the stability/instability of the investigated block; (6) It showed that the sensitiveness of the effective friction angle of the considered four types of discontinuities on the maximum X, Y, Z displacements of the key block can be listed in the following order from the most sensitive to the least sensitive: sliding planes > T2 discontinuities > T0 discontinuities > T1 discontinuities.

ARMA 15-0820
HISTORY AND MECHANISMS OF ROCK SLOPE INSTABILITY ALONG TELEGRAPH HILL, SAN FRANCISCO, CALIFORNIA

John Wallace[1], Dale Marcum[1]
[1]*Cotton, Shires and Associates, Inc.*

Telegraph Hill has a rich and colorful history extending back more than 150 years, as the fledgling city spawned from the gold rush era and emerged into one of the iconic cities of the West. The geology of this promontory on the northeastern tip of the San Francisco peninsula has resulted in an ironic twist of fate that now haunts the urban corridors that closely line its slopes. Telegraph Hill is underlain by Franciscan Complex greywacke sandstone and shale, largely unsheared, and grossly stable in its natural state. The Franciscan Complex, a series of Mesozoic accreted terranes, is composed of a heterogeneous and sheared mixture of altered volcanic rocks, chert, greywacke sandstones, limestones, serpentinites, shales, and high-pressure metamorphic rocks. Telegraph Hill however, is underlain by a largely unsheared, highly resistant, hard and strong greywacke sandstone with widely spaced interbedded shale. The high quality rock in close proximity to the burgeoning shipping industry was a valuable commodity in the mid- to late-1800s. The resistant greywacke sandstone was mined extensively for developing the seaport with seawalls and jetties along the waterfront, and for road base for the rapidly growing city. The sandstone also played an important role as ballast, steadying empty cargo ships for their return trips overseas.

The quarrying of resistant rock along Telegraph Hill has resulted in near-vertical rock faces up to 150 feet in height along the northeastern, eastern, and southern slopes. The resistant sandstone exposed along many of the old quarried slopes remains standing to this day at near-vertical angles, with the tops of these slopes retreating at very low rates. The slow retreat rates, which typically have long-term average retreat rates of less than a few inches per year, have resulted in builders gaining confidence is 'snuggling' up close to the tops and toes of these old quarry slopes. However, periodic rockslides along these slopes are a lasting reminder of the quarrying legacy. The high steep quarry walls experienced relaxation jointing from the removal of large volumes of the hillside, along with fracturing incurred as a result of the blasting. These high-angle relaxation joints and blasting fractures are sites of weathering, joint infilling, and root growth, creating apertures for surface water collection. The result is the formation of an outer rind of progressive deformation along these joints, where toppling, buckling, and planar and wedge failures occur. Telegraph Hill rockslides are most often associated with heavy rainfall events, and occur typically during or very shortly after rainfall, indicating that hydrostatic pressure is the triggering event. The resultant failures are typically shallow, rapidly moving rock slides and rock topples with high velocities and high risks to persons and property above and below the failure.

ARMA 15-0298

Effect of hydraulic diffusivity and slipping zone thickness on thermal pressurization process during seismic slip

Kimia Mortezaei[1], Farshid Vahedifard[1]
[1]Mississippi State University

Thorough understanding of the induced seismicity potential as well as the leakage probability through faults and fractured zones can facilitate full scale implementation of carbon capture and storage projects. Fault zones consist of a relatively impermeable core and a highly fractured damage zone surrounding the core. Existence of fault damage zones in reservoirs can affect the flow characteristics and the evolution of fluid overpressures. Predicting fluid-flow paths in fractured reservoirs pose a complex problem which is controlled by several parameters such as the width and density of damage zone, distribution and orientation of fractures within the damage zone. In the present work, we study the impact of damage zones on the fault response and fluid migration through a limited-dimension fault. A discrete fracture network (DFN) is used to model the natural fractured reservoir and the damage zone. The DFN model is then upscaled to acquire equivalent grid properties. The upscaled model is incorporated into coupled hydro-mechanical finite element simulations for dual-porosity medium. Two models, with and without the damage zone, are investigated. Leakage within the fault zone as well as the magnitude of induced seismic events are determined for each model. The magnitude of induced seismic events is estimated using the fault slip obtained from the numerical simulation along with seismological theories.

ARMA 15-0441

Rock slope instability modeling analysis and mitigation at mountainous road, and prediction of debris flows utilizing the satellite image, Saudi Arabia

Bahaaeldin Sadagah[1]
[1]King Abdulaziz University

ABSTRACT: Construction of mountain roads at western Saudi Arabia is a challenge, where the rock masses are high-rising, steep slopes. Al-Hada mountain road of almost 22 km long shows many incidents of rockfalls. A studied 100 m long portion of mountain road lie along a man-made and natural sharp slope cut suffers from slope failures, rockfalls incidents, mainly in rainy seasons. The rock masses are medium quality igneous rocks. The 40 m-height rock slope-cut along the road has no benches, backed by a steep natural slope. The steep man-made rock slope cut is very close to the road, forming a potentially source areas for rockfalls. The *Swedge*, *Roctopple*, and *RocFall* computer program were utilized to perform the risk analysis, modeling and mitigation on the rock slope. Satellite images shows that the gully adjacent to the rock slopes is full of water, due to the rainfall. No remedial measures taken to prevent the debris flows to take place. Input parameters such as: block size, seeder points locations of blocks falls, slope angle, restitution coefficients, and slope roughness were studied. These parameters were used to model the rock mass characteristics such as: strength, bounce height, kinetic energies, and translational and rotational velocities. The used programs modeled the proposed location, height and energy of the rockfall barriers and collectors. Modeling of the input parameters indicates the increase of the hit energy and end-point of rockfalls as the block size and restitution coefficients increases. In addition, remedial measures suggested against the run out distance of the possible debris flows.

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Technical Session 40 – Elizabethan CD
Case Histories - Mining
Wednesday, July 1, 2015, 11:00 am - 12:30 pm
Chairs: Raj Kallu & Tawanda Zvarivadza

ARMA 15-0286

The Implementation of 30 ft Wide Undercuts at TRJV

Luis Rodriguez[1], Drew Powell[1], Louis Sandbak[1]

[1]*Barrick Gold*

Increasing mining productivity is a goal to be achieved in many different ways, employing talents, techniques, and standards from many different areas, both divisional and geographical. The high quality backfill at Barrick's Turquoise Ridge Mine (TRJV) has presented the opportunity to test the potential of optimizing the dimensions of drifts mining below backfill. Other mines in Nevada have successfully mined entire levels using an optimized mining sequence that employs the use of 30' wide undercuts beneath a cemented rock fill sill. The average Rock Mass Rating of the rock mass at this mine is about 40% greater than that of TRJV. Given this situation, the question of increasing the undercut dimensions has been raised and backed with enthusiasm. This, however, does not rule out the possibility that a method practiced in one place can be directly applied to another. This situation is being approached with a high degree of conservatism in order to prove that 30' wide undercuts will be possible to mine safely at TRJV. The problems that may be faced are both operational and geotechnical, and have presented the opportunity to cooperate between departments around the mine site.

This level will be sequenced in a manner that will allow for mining to advance with 20' wide production cuts spaced apart to allow for 30' wide production cuts to be taken on retreat. In between these two stages of mining, instrumentation will be installed in two intersections and within a 30' wide cut, as well within the backfill beams between the 30' wide cuts. Mine Design Technology's multi-point borehole extensometers will be installed within the intersections to monitor displacements and pressure meters will be installed in the backfilled beams between the 30' wide undercuts. In addition, cross drift extensometer points will be installed in order to manually monitor any tunnel deformation. Numerical modelling using Map3D and Rocscience's Phase2 will be completed prior to mining to assess the stress states to be expected. A literature review involving both Mitchell and Stone equations will be completed at this time as well.

This paper will present the findings from the modelling, empirical analyses, and instrumentation, and will cover any challenges that were faced when mining this area, as well as the applicability of this mining technique in the future.

ARMA 15-0410

Evaluation and Selection of Surface and Production Casings for the New Wells at Eti Soda's Beypazari Trona Deposits

Hua Zhao[1], Bo Yu[1], Michael Hardy[1], Guray Cakmakci[2]

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Sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$) are extracted from a trona bed through solution mining at Eti Soda's Beypazari trona deposits in Turkey. Eti Soda will drill nineteen vertical wells and ten directional wells to develop ten new caverns, with an average depth of about 450 meters (m). This study evaluated potential deformation and stresses on surface and production casings for the new wells.

The two methods used for this study were: 1) FLAC3D modeling, and; 2) the method prescribed by the American Petroleum Institute/International Organization for Standardization (API/ISO). The API/ISO method is suitable for evaluating casing integrity while the casing is being run or shortly after it has been cemented. Once mining starts, however, there will usually be extra external and axial stresses concentrating on the casing due to the deformation of the surrounding rock around

the solution mining caverns. The magnitude of these stress concentrations depends on the mine plan, well layout, *in situ* stresses, and geomehancial properties of the surrounding rock. In order to evaluate casing integrity under combined loading during solution mining, a FLAC3D cavern model was developed to simulate conditions during a typical solution mining procedure inside a cavern. The numerical modeling method can analyze complicated loading conditions on the casing during solution mining, so it was used as the primary model for evaluating casing stresses. The API/ISO method was used as an ancillary method to check the competency of the selected casings, based on the modeling results.

The deformation and stresses (internal and external pressures, axial force, bending and torsional moments) on the wells were predicted from the cavern modeling. Based on the modeling results, the surface casing and the upper and lower production casings of all the vertical and directional wells were selected. The selected casings were further evaluated using the API/ISO method. The predicted high axial strains in the casings near mined-out openings resulted in casing tensile failure even when API casings of the highest grade are used. Two practices used to resolve the issue of the casing tensile failure are suggested.

This paper describes the methodology for the evaluation and selection of surface and production casings for the vertical and directional wells in detail. This study guides the selection of casings that have enough strength to withstand most loadings during their service life without an excessive degree of capacity and durability.

ARMA 15-0690

A case study for Northern Nevada single excavation! Shaft- Technical Limit: width and depth?

Arunkumar Rai[1,2], Rory Howell[1], Trent Weatherwax[1], Raj Kallu[2]

[1]Barrick Gold Corp, [2]University of Nevada Reno

Weak rock masses of high grade Carlin-trend gold mineralization are encountered in the northern Nevada. The sediments consist of very weak and altered limestone, mudstone, and carbon-rich clays which result in highly fractured nature of the rock in the region. Thus the ore body geometry, complex geology, and weak rock mass have posed tremendous challenge for the mining industry. The mining method and support design have been able to sustain with thorough study. A more recent challenge has been mines going deeper and needing bigger and better single excavation .i.e. shafts to ventilate and provide ore skipping options.

The stability concerns and shaft sinking method will be studied to evaluate the ground support needed and address with risk analysis to avoid costly and impractical decision made in the past.

The paper is an attempt to address the Geotechnical, hydrological, risk analysis to current technology and technical limits. Next five years several hundred millions dollars investment is expected for driving deeper shafts with innovative and sustainable technology to overcome current limitation. Also the author will address Engineering and support design criteria challenges to Northwest Nevada single excavation! Deep Shaft.

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ARMA 15-0717

Numerical Modeling Technique for Time Dependent Behavior of Weak Rock Masses - A Case Study

Rahul Thareja[1], Raj Kallu[1], Chase Barnard[1]

[1]University of Nevada Reno

Many Nevada gold deposits are found in highly fractured, faulted, and argillised host rock with Rock Mass Rating (RMR_{76}) mostly ranging from 10 to 50 classified as weak to very weak rock under Bieniawski's (1976) rock mass classification system. Numerical modeling techniques provide a potentially useful means for evaluation of models for a number of different geological conditions, stress conditions, and support scenarios. The study focuses on improving support design methodology employed by underground gold mines in Nevada by the application of numerical models for varying geological conditions and support scenarios. 3D numerical simulation techniques are used to gain greater insight into the behavior of weak rock mass, support mechanisms and support failure, stress conditions surrounding entries, rock-support interaction, and support performance under weak rock conditions. Time dependent numerical models are developed in 3DEC and calibrated to the displacement data procured by Multi-Point Borehole Extensometer (MPBX) arrays. Joints are embedded in the Numerical models by creation of a discrete fracture network. Parametric analysis of modeling parameters is done for confidence in parameters at various underground locations and the roof is supported by rock bolts in the numerical models to replicate the insitu squeezing behavior under stress. The modulus numbers for the numerical models were obtained by insitu plate loading tests performed in the underground mines in Nevada. Sensitivity of support design is studied with regards to elastic modulus.

ARMA 15-0852

Building a Rock Mass Model for a Large Open Pit

Felipe Capdeville-Perez[1]

[1]*Piteau Associates*

A Rock Mass Model is built based on an extensive database with different sources of information like outcrops/bench mapping, geomechanical core logging, and index and laboratory tests. After the data collection, the process continues with the compilation, validation and analysis of the data, and the definition (or later update) of the Rock Mass Units (rock materials with a distinctive mechanical behaviour). Three main components are part of a Rock Mass Model: i) Intact Rock Characterization, ii) Discontinuity Characterization (i.e. structural shear strength and character of the structural fabric) and iii) Rock Mass Characterization.

With knowing what the mechanical behaviour of the material is, there is also a need to determinate the variability of this behaviour, which is part of the heterogenic nature of the rock mass, and will be related to the confidence with this model is used by geotechnical engineers, applying sophisticated tools and/or methodologies to assess the stability of a mine design will not produce trustful design criteria if the model presents flaws, data gaps or undetermined variability.

The author's experience while building a Rock Mass model for a large open pit mine (Toquepala Mine, Southern Peru Copper Corporation, Peru) is presented. The following stages: gap analysis, data capture, validation, compilation, analysis and presentation of the model are described. Opportunities for improvement are suggested; and recommendations for the maintenance of the model are provided. This is not intended to be a proposed methodology but a particular example of Rock Mass Modeling.

Technical Session 41 – California West
Petroleum Related Rock Mechanics 1

Wednesday, July 1, 2015, 02:00 pm - 03:30 pm

Chairs: Hiroki Sone - 2 & Sherif Akl

ARMA 15-0549

Acoustic Emission Monitoring Elucidates Proppant Pack Strength Characteristics during Crush Testing

Jesse Hampton[1], Philip Nguyen[1], Vladimir Martysevich[1], Pete O'Connell[1]

[1]*Halliburton*

ABSTRACT: Enhancing formation permeability through hydraulic fracturing has become a common tool for oil and gas, as well as enhanced geothermal systems reservoir production. Nanodarcy permeability is common in unconventional oil and gas reservoirs requiring production to greatly depend on the complex network of induced and natural fractures. Proppant is used in these

complex fracture networks to keep conductive pathways open and connected to the wellbore for flowback after fracture closure. Quality and mechanical properties of proppant directly impact fracture network conductivity. Numerous proppant and proppant pack characterization tests can be performed to understand the behavior of the proppant pack in a fracture, some of which were initially outlined in API RP-56/58/60 and later in ISO 13503-2. According to ISO 13503-2 section 11, proppant pack crush strength is determined based on the amount of fines generated at specific loading conditions. This method provides estimation of proppant pack failure for a given stress range. However, there is need to develop a more comprehensive method that quantifies partial pack yielding and precise full pack crush strength. To study this problem, numerous proppant crush tests were performed according to this standard with the inclusion of acoustic emission (AE) monitoring. Two AE piezoelectric transducers were placed on the crush cell to observe sound waves stemming from grain friction as well as particle fracture initiation. The AE data was correlated to multiple parameters: stress level at granular alignment; particle fracture initiation; and proppant pack yield and strength. Testing was performed on 20/40 mesh white sand, brown sand, manmade proppant, resin pre-coated proppant, as well as other saturated and unsaturated conditions, including surface-modification agent coatings. Information gained from analysis of AE data was compared to post-test particle size distribution as well as pressure derivative analysis found in literature. As a simple, non-invasive technique, AE monitoring proved to be a valuable and effective tool in evaluating proppant pack yield and strength performance at downhole conditions, allowing a well operator to select the optimal proppant material used in the hydraulic fracturing treatments.

KEY WORDS: Proppant, Proppant Crush Test, Acoustic Emission (AE), Proppant Strength, Proppant Pack Yield Strength, Fracturing, Proppant Failure

ARMA 15-0246

Sand production delay in gas flow experiments

Pierre Cerasi[1], Andreas Berntsen[1], Lars Erik Walle[1], Euripides Papamichos[1,2]
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Testing of large, hollow cylinder specimens of a range of different sandstones has become a standard laboratory technique in SINTEF for evaluating their propensity for sand production. These tests are generally run with hollow cylinder rock specimens, with a borehole diameter of 20 mm and outer diameter of 10 cm for field cores or 20 cm for outcrop analogs. The jacketed specimen is placed in a large pressure vessel, which applies hydrostatic pressure. Feedthrough tubing connects to the outside lateral surface of the rock, and thus allows for pore pressure control and fluid flow towards the borehole, which is kept at atmospheric conditions. The test procedure involves increasing the applied hydrostatic pressure while maintaining a constant radial pore pressure gradient at the borehole wall. The resulting fluid flow (radially inwards) is responsible for production of sand whenever the confining stress is above the threshold value for sand initiation. This threshold stress can in most cases be predicted by an in-house correlation with unconfined compressive strength (UCS) with good accuracy, as long as the flowing fluid is a liquid, either oil or brine, for single phase or two-phase saturation conditions.
In sand production tests on a given rock type, where the flowing fluid is compressed air, here mimicking gas reservoir production, it appears that initial sand production occurs at higher confining stress than in tests run with liquid flow. When examining X-ray computer tomography (CT) images of the specimen post-test, it is apparent that large-scale failure of the rock has occurred during the test, although very little sand is produced, if at all.
One possible explanation is that the flowing gas desiccates the sandstone, to an extent where the rock's inherent compressive strength increases substantially. This is supported by relative humidity measurements of the air flow pre- and post-flow through the plug and related to gas expansion as it flows out of the rock into the borehole, drawing pore water from increasingly larger radii.
Another interpretation is that non-linear terms in the pressure / flow rate governing equation (Forchheimer-Ergun equation) become important at higher flows, but that only the linear pressure gradient term contributes to the gas drag force responsible for sand transport into the borehole. The

non-linear terms are speculated to be responsible for gas acceleration and deceleration through pore throats, thus making no net contribution to sand transport.

Evidence for the latter is found by careful analysis of the fluid pressure gradient at the borehole, comparing values for oil flow with gas flow. The linear term in the Forchheimer-Ergun equation for the gas case is found to yield a lower value than the corresponding term for liquid flow (where non-linear terms are negligible).

ARMA 15-0027

Microscopic observations of shale deformation from in-situ deformation experiments conducted under a scanning electron microscope.

Hiroki Sone[1], Luiz F. Morales[1], Georg Dresen[1]

[1]*GFZ Potsdam*

We deformed rock samples from Alum shale, Denmark, under the scanning electron microscope (SEM) using a deformation stage to observe and quantify the micromechanical processes occurring during fracturing and creep deformation. In the first set of experiments, a circular disc-shaped sample (about 30 mm diameter) was compressed to observe the formation of a mode I fracture as in a Brazilian disc test. A small borehole was introduced in the center to control the initiation point of the fracture. In most cases, we were able to see the formation of a thin opening fracture before the macroscopic failure by a through-going fracture. These thin fractures mostly followed grain boundaries but also propagated through some individual grains as well. Comparison with the mechanical data allows us to analyze the correspondence between the formation of these fractures and the mechanical weakening of the sample. In another configuration, a rectangular sample was compressed under sustained loads in order to observe the creep deformation of the shale samples. In these experiments, we attempt to utilize the acquired microscope images to perform digital image correlation (DIC) analysis. Such analysis allows us to directly observe the strain changes associated with the elastic deformation and creep caused by the loads, and also analyze its spatial heterogeneity. Revealing the strain heterogeneity may help to identify the minerals responsible for the time-dependent deformation. It may also be helpful to validate effective medium approaches used to predict bulk elastic properties of composite rocks from the individual properties of the constituent minerals. These models use analytical estimates of the stress- and strain-partitioning to determine the bulk properties based on fabric characteristics, but are rarely validated from direct observations. While difficulties exist in capturing images during the deformation processes, these attempts give additional insights to the micromechanical processes governing the brittle and ductile deformation of shales.

ARMA 15-0767

Comparison of Multistage to Single Stage Triaxial Tests

Malik Alsalman[1], Michael Myers [1], Munir Sharaf-Aldin[2]

[1]*University of Houston,* [2]*Metarock Laboratories*

The standard test used to determine the calibration of a linear elastic material models is called the single stage tri-axial (SST) test. In this test, the confining stress is held constant while the axial load is increased until the sample reaches the maximum compressional strength (MCS) as shown in **Error! Reference source not found.**.

In contrast we are proposing the use of the multistage tri-axial (MST) test. Here multiple confining stresses are applied to a single sample and the axial load is increased as shown in **Error! Reference source not found.**. Instead of increasing the axial stress until sample failure, the axial load is ramped until the point of positive dilatancy (PPD). The PPD is where the slope of the deviatoric stress versus volume strain curve changes its sign as shown **Error! Reference source not found.**.

Conventional tri-axial test results will differ from those obtained from multistage tri-axial tests. The purpose of this study is to investigate the relationship between the two test protocols. We used different types of rocks (Shale, Sandstone, Chalk) in our study with a total of more than 30 tests, and compare the results of both test types in terms of Young's Modulus, Poisson's Ratio, MCS, PPD, energy (the integrated rate of plastic work), friction angle, and cohesion. **Error! eference source not found.** shows a typical example of the comparison of the Mohr-Coulomb plots for Mancos Shale. The stiffness represented by Young's Modulus changes between the two tests as shown in Figure 5 and Figure 6 respectively.

This paper presents a methodology for correcting the cohesion and the friction angle from multi-stage tests to single stage test equivalents for each lithology type. The paper concludes with the techniques and measurements required to correct the multi-stage test results to those obtained from a single stage test protocol.

ARMA 15-0496

Dilatancy of clay shales and its impact on pore pressure evolution and effective stress for different triaxial stress paths

Katrin Wild[1], Florian Amann[1], Derek Martin[2], Jerome Wassermann[3], Christian David[3], Marco Barla[4]

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Clay shales are amongst the most difficult rock types in terms of characterizing their effective strength and stiffness properties and modeling their short- and long-term deformations associated with stress perturbation due to drilling or tunneling. Due to their often extreme low permeability, excess pore pressure develops during short-term loading associated with the tendency of the material to dilate or contract. A recent laboratory study utilizing a standard triaxial stress path (i.e. confinement is held constant as the axial load is increased) suggests that pore pressure changes are primarily controlled by the transversal isotropic elastic behavior at low compressive loads, and the tendency of the clay shale to dilate as the compressive stress exceeds the dilatancy threshold. In addition, both, poro-elastic properties (including Skempton's coefficient) and the tendency of the clay shale to dilate depend strongly on the confining stress. At higher confining stress the peak pore pressure occurs nearly contemporaneous to the peak stress. As the confining stress decreases the peak pore pressure occurs substantially before the peak strength. For the latter case pore pressure changes have a positive effect on the effective strength. However, the stress path utilized in standard triaxial tests may substantially differ from the stress path associated with drilling or tunneling, and its influence on the effective strength is to date poorly understood.
Based on a comprehensive laboratory study on back-saturated clay shales this contribution shows 1) the influence of confining stress on poro-elastic properties of the Opalinus Clay shale, 2) the confining stress dependent dilatancy and related pore pressure effect, and 3) the influence of stress path on the pore pressure response and related effective strength properties. For the latter triaxial tests utilizing a pure shear compression stress path were used. This stress path is equal to the plain strain stress path around a circular opening in an isotropic elastic medium and isotropic far field stress conditions and is considered a reasonable approximation for the stress path associated with drilling or tunneling operation.

ARMA 15-0237

Experimental investigation of cement to rock bonding

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Recent work has identified the well cement to rock interface as the weakest link, when it comes to leakage from wells. This leakage occurs for many older production wells, not necessarily from the target production reservoir, but often from higher, pressurised permeable layers. Ongoing work at SINTEF has focused on cement bond shear strength measurement, using the punch-out method. In this work, we look at fundamental measurement of failure under compression and tension of a relatively smooth cement to rock interface. This will give us much needed input data for numerical modelling, where shear strength, friction angle, failure angle and not least tensile strength of the cement bond are vital parameters. These parameters will then allow us to simulate realistic downhole stress path scenarios and help quantify conditions leading to leakage path formation as a function of cement type and rock formation.

The performed tests resulted in either shear of the cement interface under various normal loads or tensile stressing of the interface under direct tension loading. The tests were thus conducted in a load frame under uniaxial compression or direct tension mode. For the compression tests, inclined surfaces were cut from originally cylindrical Berea sandstone plugs, of 1.5" diameter. These planar surfaces were cut at different angles with respect to the plug's axis. Portland class G cement was then poured in a heat shrink sleeve, on the top of the pre-cut rock in order to reconstitute a cylindrical plug. The rock/cement mixture was then placed in a metal pre-compaction casing under 20 MPa uniaxial stress and 60 °C for 24h to 72h. Plugs created in this manner were kept in an oven for further curing at 60 °C over several days.

Under uniaxial compression testing, the different plugs were submitted to stress states departing further and further from pure shear conditions, at the cement to rock interface; this, the more this surface departed in orientation from the corresponding failure angle of the composite system.

For the direct tension tests, plugs were prepared in a similar manner as above, only that the interface was prepared with a surface angle of 0 degrees with respect to the plug's axis (that is, parallel to the end surfaces of the composite plug). The tests were then run in uniaxial tension mode.

Technical Session 42 – California East Shale - Experiments and Modeling

Wednesday, July 1, 2015, 02:00 pm - 03:30 pm

Chair: TBD

ARMA 15-0225

Modeling of Failure Behavior of Anisotropic Shale Using Lattice Discrete Particle Model

Weixin Li[1], Congrui Jin[2], Marco Salviato[2], Gianluca Cusatis[2]

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With the rapid growth of the shale gas/oil industry, especially the development of hydraulic fracturing technique, the study to promote deep understanding of the mechanical properties of shale-like rocks is becoming more important. Of particular interest is the development of adequate numerical model to capture the heterogeneity and anisotropy of shales, in order to accurately predict and optimize the fracturing process.

The Lattice Discrete Particle Model (LDPM), formulated by Prof. Cusatis, is an effective model to simulate the failure behavior of quasi-brittle materials. LDPM modeling reproduces material internal structure at the meso-scale considered to be the length scale of coarse aggregate pieces. The meso-structure deformation is described through the adoption of rigid-body kinematics for each aggregate particle in the framework of discrete models. The mechanical interaction among particles is governed by meso-scale constitutive equations that simulates fracturing behavior, material compaction due to pore collapse and frictional shearing. LDPM has been proven to be a powerful tool to accurately predict concrete behavior under various loading conditions both in tension and unconfined, confined and hydrostatic compression. Because of its inherent heterogeneity, LDPM has promising potential to also reproduce nonlinear behavior of highly heterogeneous and anisotropic rocks.

In this work, LDPM is extended to capture the material anisotropy of shales due to the partial alignment of anisotropic clay minerals and naturally formed bedding planes. Especially, bedding planes can act as weak zones where fractures propagate along. Through an approximated geometric description of shale internal structure, LDPM can address the effect of the anisotropic angle between bedding planes and the loading direction on different failure modes. Calibration and validation is performed by comparing the numerical simulation results with experimental data. A series of simulated experiments, including Brazilian test, unconfined compression test and three point bending test, are demonstrated. This work will pave the way for the development of reliable hydraulic fracturing models that appropriately account for the mechanical behaviors of heterogeneous and anisotropic shale.

ARMA 15-0389

Experimental Investigation of Hydraulic Fracturing of Shale with water

J. William Carey[1], Esteban Rougier[1], Zhou Lei[1], Hari Viswanthan[1]
[1]Los Alamos National Laboratory

The use of supercritical CO_2 as a hydraulic fracturing fluid for shale gas has potential advantages in terms of enhanced hydrocarbon production and the possibility of co-sequestration of the trapped and adsorbed CO_2. Low viscosity in combination with miscibility with hydrocarbon provides plausible mechanisms for effectively extracting hydrocarbon from tight fracture networks. By analogy with coal bed methane, we also expect to sequester CO_2 by adsorption processes to kerogen and clay as well as by permanent loss of CO_2 to the fracture network. In this study, we use a combination of experimental and computational approaches to study fracture generation and permeability during injection of supercritical CO_2.

The experiments were conducted on Utica shale, a shale gas play in northeastern US, using a triaxial coreflood device at temperatures from 25-50 °C and confining pressures from 35 to 200 bars. Three different methods of fracture generation were used: compression, direct shear, and hydraulic fracturing in order to span a range of fracture types. Permeability was measured continuously during deformation and was monitored following fracture events as a function of continuing deformation and hydrostatic pressure. Fractures propagating parallel to bedding were an order of magnitude more transmissive than fractures propagating perpendicular to layers. Significant deformation (generally >1% to as high as 10%) was required to produce discrete fracture events. Fracture geometry was characterized using x-ray tomography before and after the experiments. Fractures propagating in the plane of the shear axis had a much simpler geometry. We used the experimental results to develop finite element/discrete element computational methods that simulate fracture propagation in shale under differing stress environments and in response to the presence of injected fluids.

ARMA 15-0312

FDEM simulation on a triaxial core-flood experiment of shale

Zhou Lei[1], Esteban Rougier[1], Earl Knight[1], Antonio Munjiza[2], William Carey[1], Hari Viswanathan[1]
[1]Los Alamos National Laboratory, [2]Queen Mary, university of London

Hydraulic fracturing (hydrofrac) is a very successful method that has been used to extract oil and gas from tight rocks like shale for a number of decades. However, there are still many aspects related to hydrofrac operations and how they affect the hydrocarbon's recovery levels that remain poorly understood. This is reinforced by reports from industry experts that estimate that for a single $10 million dollar lateral wellbore fracking operation, only 10% of the hydrocarbons contained in the rock can be extracted. In an effort to better understand how to improve hydrofrac recovery efficiencies and to lower its costs, LANL recently funded the Laboratory Directed Research and Development (LDRD) project: "Discovery Science of Hydraulic Fracturing: Innovative Working Fluids and Their Interactions with Rocks, Fractures, and Hydrocarbons". Under the support of this project, the LDRD modeling team is working in conjunction with the experimental team to improve the understanding of fracture initiation and propagation in shale rocks. The tool of choice for the modeling team was a combined finite-discrete element based hydro mechanical simulation code. In the context of rock mechanics, the combined finite-discrete element method (FDEM) has been applied to many complex industrial problems such as block caving, deep mining techniques, rock blasting, seismic wave propagation, packing problems, dam stability, rock slope stability, rock mass strength characterization problems, etc. The extension of the FDEM by the addition of the effects of the fluid pressure on the fracture faces presents us with a very promising platform for the study of this type of problems. The experimental team conducted direct shear experiments in a triaxial coreflood system. After the experiments were conducted, the samples were taken into an x-ray tomography unit to obtain detailed images depicting the fracture patterns inside of them. In this work, the sensitivity of the obtained fracture patterns to uncertainties and/or changes in the boundary conditions is demonstrated using FDEM. Simulation results in comparison with the triaxial core flooding experiments will be presented.

ARMA 15-0520

NUMERICAL SIMULATION STUDY ON CO2 INJECTION FOR ENHANCING HYDROCARBON RECOVERY AND SEQUESTRATION IN TIGHT OIL FORMATIONS

Sumeer kalra[1], Dr. Xingru Wu[1]
[1] *University of Oklahoma*

Hydrocarbon resources from unconventional reservoirs especially tight/shale plays, are changing the North America's energy prospect. Single digit percentage of oil shale recovery with current best practices, leaves a large room for recovery improvement. While aqueous phase injection into shale formation is extremely challenging, other recovery techniques need to be evaluated and pilot tested for secondary recovery in oil shale reservoirs. Injecting Carbon Dioxide (CO_2) into oil shale formations can potentially improve oil recovery. Furthermore, the large surface area in the organic rich shale could permanently store CO_2 volume without jeopardizing the formation integrity.
This work is a study on evaluating the effectiveness of CO_2 enhanced oil shale recovery and shale formation CO_2 sequestration capacity. The work identified the most favorable reservoir properties and operating envelop for field application of CO_2-EOR in tight formations. A compositional reservoir simulator is used to model CO_2 injection in an oil shale reservoir. Formation and petrophysical properties, reservoir fluid data of the Bakken formation is used to set up the base model for simulation. For investigating the technical feasibility of increasing oil production by CO_2 injection, a sector of Parshall field from Bakken formation is modeled with two active wells. The reservoir model considered petrophysical characteristics of shale formation that affects CO2 flow migration such as (1) reservoir heterogeneity (2) in-situ stress change (geomechanical) impact on permeability of natural fracture networks and hydraulic fractures during simultaneous injection and production, (3) impact of adsorption and diffusion on carbon storage in organic rich shale, (4) presence of natural fractures, secondary fracture geometry and connectivity, fracture density and orientation effect.
The results are based on sensitivity analysis of the characteristic shale petrophysical, geomechanical properties and displacement mechanisms. Sensitivity analysis also focused on injection schemes and completion practices for most economic field applications. Sensitivity analysis is implemented by two methods. Method one analyzed each parameter individually and reproduced the results in terms of a tornado chart, defining the critical parameters. Method two analyzed all uncertain parameters together using the Design of Experiment (DoE) and Response Surface Modeling (RSM) approach to counter the interaction between parameters and influential parameters into generating a proxy model for optimizing oil recovery and CO2 injection into the formation. The above studies are implemented with and without geomechanical module and results are analyzed.
The results show that facilitating oil recovery from shale reservoirs by CO_2 injection is much higher than primary depletion depending on fracture network connectivity and geomechanical impact. This study outlined the capabilities of CO_2 injection for improving oil production from unconventional reservoirs. Also, significant CO_2 storage capacity if applicable in shale formations, will be a major step towards advances in CO_2 sequestration in widely spread shale reservoirs

ARMA 15-0653

Modeling Stray Gas Leakage from Wellbores in Colorado Shale Gas Operations

Greg Lackey[1], Harihar Rajaram[1], Satish Karra[2], Hari Viswanathan[2]

[1]University of Colorado, Boulder, [2]Los Alamos National Laboratory

Over the last ten years, the extraction of resources from unconventional formations has fueled a significant rise in U.S. oil and natural gas production. Public concern with the potential environmental impacts of the extraction process has increased as well. In particular, debates have arisen about the fate of the chemicals used in the high volume slick water hydraulic fracturing. As a result, a number of studies have begun to investigate the quality of groundwater in regions with heavy unconventional oil and gas development. These studies have found varying degrees of methane in the shallow subsurface in the vicinity of oil and gas wells. Although methane itself is not hazardous to human health, unless present in explosive quantities, its isotopic signature allows for the gas to be used as a tracer. Thus, the presence of methane with a thermogenic isotopic signature in the shallow subsurface potentially indicates contamination from oil and gas drilling operations. The uncemented annulus of the wellbore is a possible pathway for migration of thermogenic methane into the shallow subsurface. Poorly cemented wells allow for methane to migrate upwards from the producing formation and accumulate in the annulus between the production casing and the surrounding rock matrix. Additionally, methane from intermediate formations above the target formation may also leak methane into the annulus if they are not sealed off by cement. In the U.S., the annulus of the well is capped at the surface by the bradenhead valve to prevent the venting of methane to the atmosphere. However, it allows the gas to build and increase the pressure in the annulus. We present modeling results for the behavior of methane gas that has accumulated in the annulus and its interaction with the surrounding subsurface. We use previously derived analytical models of multiphase flow in an annulus to set the boundary conditions for numerical simulations. We simulate two phase methane-water flow in the region surrounding the well using the numerical model PFLOTRAN. A number of scenarios are considered with varying degrees of gas leakage and fracturing in the subsurface. Our models illustrate the relationship between methane in the uncemented annulus and in the surrounding formation, the influence of a sealed bradenhead on methane migration, and the mechanisms of methane transport in the subsurface along fractures and through formations.

ARMA 15-0228

Gas Transport Characterization of Fractured Rock by In-situ Gas-injection Tests

Michito Shimo[1], Susumu Shimaya[2], Toshio Maejima[3]

[1]Fukada Geological Institute, [2]Taisei Corporation, [3]Former Japan Oil, Gas and Metals National Corporation

Gas transport characteristics of fractured rocks is a great concern to variety of engineering applications such as LPG underground storage, nuclear waste disposal, CCS and gas flooding in the oil field.

Besides absolute permeability, relative permeability and capillary pressure as a function of wetting phase saturation, including threshold pressure, have direct influences to the results of two phase flow simulation. However, number of the reported gas flow tests for fractured rocks are limited.

The authors will present the results of two types of in-situ gas injection tests, with different scales, a borehole test and a chamber test conducted in fractured granitic rock at the Japanese underground LPG storage cavern construction site.

Applicability of the two-phase flow parameters for fractured rock will be also discussed based on the simulations using TOUGH2.

Technical Session 43 – Elizabethan AB
Tunnels and Caverns 2

Wednesday, July 1, 2015, 02:00 pm - 03:30 pm

Chairs: zixin zhang & Qi Zhang

ARMA 15-0137

A new 3D constitutive model for rock mass tunnel

Qi Zhang[1], Hehua Zhu[2], Lianyang Zhang[3], Boqi Huang[2]

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A new constitutive model is proposed based on the modified generalized three-dimensional (3D) Hoek-Brown strength criterion, which was proposed by Zhang and Zhu (2007) and modified by Zhang et al. (2013). This model involves a multi-stage plasticity flow rule that varies with the Lode angle and level of intermediate and minor principal stress. This model also considers the effect of the intermediate principal stress with a 3D plasticity flow rule. In the 3D tension condition, at which the material would yield in the direction of the tensile traction, the radial flow rule is prescribed. In the 3D compression condition, for a low intermediate and minor principal stress, at which a large rate of is exhibited, an associated flow rule is applied. Meanwhile, for a high stress, at which the material no longer dilates at failure, a constant-volume flow rule is prescribed. The new model is embedded in the three-dimensional finite element software (GeoFBA3D). An application example of the tunnel is provided and compared with the model based on Hoek-Brown criterion.

ARMA 15-0209

Salt Structure Information System (InSpEE) as a Supporting Tool for Evaluation of Storage Capacity of Caverns for Renewable Energies - Rock Mechanical Design for CAES and H_2 Storage Caverns

Dirk Zapf[1], Kurt Staudtmeister[1], Reinhard Rokahr[1], Sabine Donadei[2], Dirk Zander-Schiebenhöfer[2], Peter-Laszlo Horvath[2], Stephanie Fleig[3], Lukas Pollok[3], Markus Hölzner[3], Jörg Hammer[3]

[1]Leibniz University of Hannover, [2]KBB Underground Technologies GmbH, [3]Federal Institute for Geosciences and Natural Resources (BGR)

The increasing production of excess energy from fluctuating renewable energy sources raises the question of large-scale energy storage. Therefore, energy storage power plants, which generate, feed and withdraw renewable electricity from compressed air or hydrogen on demand, play an essential role. Large-volume storage of these media can only be accommodated in deep geological formations. A high degree of flexibility in operation and an extremely low tendency to react with the stored medium, make salt storage caverns the preferred storage option. However, existing and available estimates of their total potential for energy storage are insufficiently substantiated.

The objectives of the InSpEE project are, therefore, the development and deployment of design principles and basic geological/geotechnical data and of site selection criteria for the establishment of salt caverns as well as the estimation of the renewable energy storage potentials of the salt structures in the North German Basin.

Cooperating InSpEE project partners are the Federal Institute for Geosciences and Natural Resources (BGR), Leibniz University of Hanover, Institute of Geotechnical Engineering/Department of Underground Construction (IGtH) and KBB Underground Technologies GmbH (KBB UT) bringing in their expertise in the areas of salt geology and rock mechanics. Besides systematic collection and evaluation of geological information about salt deposits in North-West Germany thermo–mechanically based assessment criteria will be applied for the site characterization and estimate of its possible storage potential. At the end of the three-year project period in 2015, a publicly accessible “Salt information system” will be provided and in addition, the

storage potential for caverns as well as for hydrogen and compressed air in Northern Germany shall be addressed.
In the proposed paper the rock mechanical design with respect to the stress state in the vicinity of an CAES and H_2 storage in salt caverns under consideration of thermo-mechanical coupled calculations will be presented. The results of the rock mechanical calculations are an essential basis for the review and the assessment of the storage potential of renewable energies in Northern Germany.

ARMA 15-0358

Soft Ground Shield Driven Tunnel Defect Analysis

Pan Li[1], Peixin Shi[1]
[1]*School of Urban Rail Transportation, Soochow University*

The subway mileage has increased dramatically worldwide, especially in China, in the past decades and will be continuously increasing in the next decades driven by the demands on underground space usage and advancement of tunneling technique. Subway tunnels are vulnerable to a variety of defects which, individually or interactively, deteriorate the tunnel function for providing passengers with a safe and comfortable transportation means. Effective tunnel maintenance can slow down tunnel defect generation and prevent tunnel defects from developing into catastrophic structural failure. This paper provides theory and practice guidance for tunnel proactive maintenance which includes both preventive and predictive aspects of maintenance. The paper summarizes typical tunnel defects and major contributing factors to tunnel defect generation based on the findings from an inspection program for 130 km of subway and roadway tunnels in eastern part of China. The mechanism of tunnel functional degradation is explored associated with five critical elements: environment, structure, components, connections, and material, consisting of a tunnel operation system. The five elements individually deteriorate with time and interactively degrade tunnel function. A tunnel general condition rating system is proposed based on the quantitative indices for evaluating the condition of the five individual elements. The available analytical, numerical, instrumentation, and testing tools for obtaining the element condition indices are discussed. The guidance for tunnel proactive maintenance practices is recommended using the general tunnel condition ratings. The research findings from this paper lay a good foundation for future tunnel maintenance.

ARMA 15-0467

Numerical study on long-time deformation characteristics of soft clay around subway tunnel under train vibration load

Bin Ye[1], Shutao Pu[1]
[1]*Tongji University*

In recent years, subway has developed rapidly in many cities of China. However, the environmental problems caused by train vibration load, such as the large settlement of surrounding ground around tunnels, can't be ignored. The subway tunnels in shanghai mainly lie in the 3^{rd} layer of muddy-silty clay or the 4^{th} layer of muddy clay. These two layers of clay were especially soft and sensitive to vibration load. In this paper, a numerical study on long-time deformation characteristics of soft clay around the tunnel of Shanghai Metro Line 9 under train vibration load was presented. The numerical simulation adopted an elastic-plastic constitutive model that can take into account the long-term accumulation of soil deformation and excess pore water pressure under a huge number of cyclic loadings. The simulated results, including long-time displacement of soils around the tunnel, ground surface subsidence, and the variation of excess pore water pressure, were analyzed and discussed. The final settlement of surrounding ground was predicted through analyzing the variation tendency of maximum vertical displacement of soil. By comparing the simulated results and the measured data, it was proved that the simulated results were consistent with the measured data. Therefore, the long-term deformation of soil around subway tunnels under vibration load can be evaluated and predicted by the numerical method presented in this paper.

Keywords: subway tunnel; vibration load; soil deformation; numerical simulation

ARMA 15-0836

Optimization of Pipe Roof Design for Gongbei Port Tunnel Excavation

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[1]School of Urban Rail Transportation, Soochow University, [2]China Railway 18th Bureau Group Co Ltd

Abstract:

The Gongbei Port tunnel is a critical component of the Hong Kong-Zhuhai-Macau Bridge, currently the largest construction project in China, connecting Hong Kong, Macau, and Zhuhai with a series of bridges and tunnels. It is a double deck, three-lane in each direction roadway tunnel with a length of 255 m, cross-sectional area of 345 m^2 and approximate alignment curvature of 900 m. The tunnel is buried within soft sandy/silty clay about 4 to 5 m below the ground surface at Gongbei Customer Port. The poor ground condition, shallow burial depth, large opening area, small alignment curvature, and political sensitivity of the construction site create a big engineering challenge for risk control associated with ground movement.

To limit the ground movement and reduce the construction risk, the preliminary design proposed to excavate the tunnel using conventional method with a pipe roof in combination with artificial ground freezing as excavation support. The pipe roof consists of 10-ϕ1800 mm and 30-ϕ1400 mm steel pipes. During the construction phase, an optimization of the pipe roof design is conducted based on the contractor's local construction experience, construction experience of case history projects from other contractors, field slurry pipe jacking tests, and numerical simulations. The optimized construction plan proposed to use 36 steel pipes with a uniform diameter of 1620 mm as the roof support, while adjust the pipe layouts and optimize the jacking and receiving construction organization plan. The new pipe roof construction plan is proved to satisfy the strength and stability requirement of the excavation support system, reduce the construction cost and equipment investment, shorten the construction duration and more confidently control the risk associated with the alignment accuracy and ground movement. The optimization of the pipe roof design of the Gongbei Port tunnel excavation expands the conventional tunneling technique by using unprecedented large pipe roof supporting system along curved alignment and provides valuable case history experience for the future projects.

Keywords: Tunnel Excavation, Pipe Roof, Slurry Pipe Jacking, Ground Freezing

ARMA 15-0179

A micromechanical study of the interactions between a hole and a crack under compression using PFC2D

Shuai Zhou[1,2], J. Woody Ju[1,2], Hehua Zhu[1,3,4], Zhiguo Yan[1,3,4], Qing Chen[1,4], Zeyu Dong[1,4]
[1]Department of Geotechnical Engineering, Tongji University, [2]Department of Civil and Environmental Engineering, University of California, Los Angeles, [3]State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, [4]Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University

The interactions between defects are important in the behavior of brittle materials. The micromechanical interactions between a hole and a crack under uniaxial compression are investigated in this paper. Experiments of samples containing a hole and a crack are conducted. Subsequently, Particle Flow Code 2D (PFC2D) is adopted to simulate the fracture behavior. The crack initiation, propagation and coalescence with a hole are investigated, such as the type and the initiation stress of the first crack and the secondary crack. Different geometric configurations are considered. The ligament length (S) and the inclination angle (α) have different effects on the underlying failure phenomena. The propagating cracks contain the first cracks and secondary cracks. The first crack initiation stress will increase with the inclination angle when the inclination angle is more than 30°. The first cracks are initiated at crack tips with a steep inclination angle and on crack surface with a shallow inclination angle. Both the first cracks and secondary cracks will disturb the stress field and

displacement field. The DEM simulation explains the initiation position of secondary cracks observed in experiments, which is not necessarily located at the crack tips or on crack surfaces, but possibly in the intact part of the specimen at a distance away from the pre-existing crack. A greater distance between the hole and pre-existing crack will lead to a larger first crack initiation stress. The secondary cracks usually propagate as shear cracks in the same plane. However, depending on the geometry, the secondary cracks also propagate out of plane as either tensile or shear cracks. The hole will influence the crack initiation stress of the pre-existing crack and attract the propagating cracks. The present research paves the way for using the DEM to simulate the micromechanical interactions between a hole and a crack.

KEYWORDS: micromechanical interaction; a hole and a crack; PFC2D simulation; compressive loading

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Technical Session 44 – Elizabethan CD
Fracture Mechanics 1

Wednesday, July 1, 2015, 02:00 pm - 03:30 pm

Chairs: Andy Rathbun & Xiaodong Ma

ARMA 15-0190

Experimental Demonstration of Delayed Initiation of Hydraulic Fractures below Breakdown Pressure in Granite

Guanyi Lu[1], Efosa Uwaifo[2], Brandon Ames[2], Arinzechukwu Ufondu[2], Andrew Bunger[1,2], Romain Prioul[3], Gallyam Aidagulov[4]

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Under the assumption of classical hydraulic fracture breakdown models (Haimson and Fairhurst 1967,"H-F" and Hubbert and Willis 1957,"H-W"), the near wellbore tensile stress induced by fluid pressure which is less than the tensile strength of rock formation will never cause the initiation of hydraulic fracture. However, rocks can be caused to fail in a delayed manner under a stress well below its strength. This behaviour, generically referred to as "static fatigue", has been verified for rock and many other materials through decades of laboratory experimentation. Theoretically, then, static fatigue should allow for hydraulic fracture initiation at wellbore pressures below the pressure required for instantaneous fracture initiation. Here we present laboratory observations and measurements demonstrating this phenomenon in Coldspring Charcoal Granite specimens. In these experiments, we pressurize a 50 mm long open section of a 12.5 mm diameter wellbore drilled through the center of 150 mm cubic specimens that, for this series of experiments, are subject to zero external confining stress. Consistent with typical static fatigue behaviour, as well as with a static fatigue law implied by 4-point bending tests we performed on beams of the Charcoal Granite, we observe an exponential increase in the time to initiation as the wellbore pressure is decreased.

After Detournay and Carbonell (1997), we recognize that classical models H-W and H-F are valid in the limit of fast and slow pressurization, where "fast" refers to the case where fluid does not penetrate the flaws and pore spaces of the rock in the vicinity of the wellbore and "slow" refers to the case where it does. Bunger and Lu (2014) predict that delayed hydraulic fracture initiation will also be profoundly affected by the transition from fast pressurization for the short time to failure cases to slow pressurization for the long time to failure cases. After initially demonstrating the concept of delayed initiation, we will then present another series of experiments using a much higher viscosity fluid. We show that higher viscosity leads to larger instantaneous breakdown pressure and a more rapid increase in time to failure with decreasing wellbore pressure, both of which are observations that are consistent with the predicted role of penetration on delayed hydraulic fracture initiation.

ARMA 15-0313
FDEM SIMULATION ON FRACTURE COALESCENCE IN BRITTLE MATERIALS
Earl Knight[1], Zhou Lei[1], Esteban Rougier[1], Antonio Munjiza[2]
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As the name indicates, the FDEM bridges the gap between finite and discrete element methods. As such, it has become a tool of choice for simulating problems involving fracturing, fragmenting and complex shapes. Some of the key advantages of FDEM are: the introduction of finite displacements, finite rotations, and finite strain based deformability combined with suitable material laws; the incorporation of discrete element based transient dynamics, contact detection, and contact interaction solutions and objective discrete crack initiation and crack propagation solutions that have a great deal of fidelity in reproducing complex fracture patterns and eventual fragmentation.

The examples presented in this paper consist of compression virtual experiments conducted on specimens that have two or more pre-existing fractures inside them. These fractures are arranged through the thickness of the specimens following different geometrical layouts. Two different test series were performed: one under uniaxial loading and one under biaxial loading with different levels of confining stresses being applied. Some of the main features of the fracture propagation processes reported in this work are: initiation of wing cracks and secondary cracks; direction and propagation of the newly generated cracks and patterns of fracture coalescence. Relationships between the initial geometries (e.g. the number, the orientation and the length of the pre-existing fractures, the distance between the pre-existing fractures, etc.) and the pattern of fracture coalescence are also presented. Finally, the results obtained in the simulations are qualitatively compared with experimental observations reported in the literature.

ARMA 15-0746
Critical pressure and scaling in cavity expansion tests
Ali Tarokh[1], Derrick Blanksma[2], Ali Fakhimi[3], Joseph Labuz[1]
[1]University of Minnesota, [2]Itasca Consulting Group, [3]New Mexico Tech

The study of fracture initiation from a cavity in rock has been largely motivated by the extraction of petroleum and natural gas from a borehole and therefore, is often considered as one of the most challenging problems in rock mechanics. An unresolved issue is relating the fracture parameters from small scale laboratory test to a large scale engineering process. To investigate fracture initiation from a borehole, cavity expansion tests were conducted in the laboratory on specimens of Berea sandstone. To capture the failure process near the circular cavity, digital image correlation was used. In addition, a two dimensional bonded particle model was developed and validated. For investigating the effect of scaling on fracture parameters (*e.g.* critical pressure), several larger specimens with different tension softening behavior were tested numerically and the fracture process zone dimensions were studied It was shown that size effect plays an important role. Also using the DIC measurements, it was found that a fracture develops at 80% of peak internal pressure. Figs. 1a and 1b compare the induced fractures in the physical and numerical tests.

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ARMA 15-0420
An Investigation of Rough Surface Closure with Application to Fracturing
Amirhossein Kamali[1], Maysam Pournik[1]
[1]University of Oklahoma
Natural fractures, hydraulically generated fractures, and acid etched fractures have some degree of fracture face roughness that generates flow conductivity. While the roughness of naturally fractured and hydraulically fractured faces are limited in extent and in conductivity generation, acid etched fractured faces can have substantial roughness with significant fracture conductivity. While it has been proven both theoretically and experimentally that fracture conductivity depends on fracture face roughness, there are limited models that can predict fracture conductivity at different closure stresses

for these various fracture roughness patterns. In addition, some of the models require detailed statistical and topographical surface profile parameters, which limit their field application.

A numerical model is developed to study the closure of rough surfaces in contact. Both asperities and semi-infinite half-spaces are assumed to be deformable. The mechanical interaction among the asperities, which is a consequence of half-space deformation, is accounted for and its effect on the fracture closure is investigated. Asperity failure is also considered in the model and the results are compared to that of perfectly elastic contact. Aperture profiles that are the output of the closure model is used to solve the fluid flow problem and study the effect of closure stress on fracture conductivity for various initial fracture face roughness patterns.

Modeling results indicate that most fracture closure takes place earlier on at lower stress levels. This could be due to the fact that there are fewer asperities initially in contact. It is also evident in our results that the closure behavior depends on the etching pattern as well as the elastic properties of the surface. The performance of a rough fracture depends on its initial aperture, asperity height distribution, roughness pattern and the closure stress range. Certain fracture roughness patterns were able to withstand the closure stress while undergoing lesser amounts of closure.

This paper discusses the closure of fractures and attempts to shed more light on the performance of such stimulation technique by comparing the closure behavior of some particular surface patterns. Our model can be used to determine the most optimum fracture system for a given reservoir condition and hence guide the stimulation design to achieve the desired fracture pattern.

ARMA 15-0030

Advances in the Use of New-Age Complex Fracture Modeling, Earth Modeling, and Reservoir Simulation Tools as an Asset Well Planning Tool

Eric Holderby[1], Jeff Dahl[2], Ron Dusterhoft[1], Shameem Siddiqui[3], Carla Eichler[1], Jeffrey Yarus[4]

[1]Halliburton, [2]Devon Energy, [3]Pinnacle - A Halliburton Service, [4]Halliburton - Landmark

Recent advances in complex fracture modeling capabilities have provided multiple realizations of the development of fracture networks in unconventional reservoirs. This has allowed for calibrated fracture network geometry definition in reservoirs that are conducive to fracture network growth in multiple directions due to in-situ reservoir conditions such as the presence of natural fractures and low horizontal stress anisotropy. The ability to predict fracture network creation in these conditions has also allowed for hydraulic fracturing design optimization focusing on net pressure development to achieve the desired complexity. Increases in fracture complexity development can result in increased production results in certain reservoir conditions, especially in low permeability unconventional reservoirs with two-phase hydrocarbon production. While this analysis capability has led to positive results, there is a desire within the unconventional arena to increase collaborative development of assets for even greater improvement and increased understanding of optimized exploitation of these assets. For this reason the ability to include the resulting realizations of complex fracture networks in a three-dimensional asset description would prove invaluable to asset development and well planning, and further increase a collaborative understanding across various disciplines such as asset evaluation, geosciences, drilling, completions, and production. Also continual asset management focusing on re-stimulation, in-field well drilling, and reservoir production monitoring would greatly benefit from incorporating these fracture networks in an ever evolving earth model.

The significant benefits of being able to incorporate results of complex fracture modeling and geomechanical descriptions within a geological/geophysical earth model platform has led to the development of an analysis process combining the results of multi-disciplinary modeling techniques focused on unconventional shale assets. This paper describes these different analysis tools and outlines a multi-disciplinary process for using this knowledge for asset development, well planning, and completions optimization.

ARMA 15-0489

The Brittleness Index in Hydraulic Fracturing

Panos Papanastasiou[1], Colin Atkinson[2]
[1]University of Cyprus, [2]Imperial College of Science

The Brittleness index of rocks is often used as a criterion for candidate selection of rock intervals for hydraulic fracturing in shale reservoirs. Several definitions for measuring the brittleness of the rocks were proposed based on different mechanical properties of rocks that are derived from the stress-strain curve or from correlations with physical properties. An inherent problem with some proposed definitions, which are based on simple definitions that were not derived from scientific principles, is that they do not follow the expected trend with some varying parameters such as the confining pressure. Therefore, in unconventional shale reservoirs is important to understand how britlleness can be represented and be used for practical applications of hydraulic fracturing.
In this work we propose a new definition of a brittleness index which is a combination of material strength parameters and insitu stresses. This definition was derived from an analytical model of hydraulic fracturing in weak formations which accounts for plasticity near a propagating hydraulic fracture. The model is based on dislocation theory that accounts for the large scale plasticity that surrounds the crack tip. The effect of distributed plasticity is replaced by super-dislocations that are placed in the effective centres of the complete slip process that is distributed around the crack tip. The new brittleness index varies between 0 and 1 with the value 0 to correspond to brittle propagation and 1 to a fracture that requires infinite energy release per unit advance. The values between 0 and 1 correspond to fracture propagation of increasing ductility from brittle to small scale and finally to large scale yielding. The obtained results are useful for the understanding and the modeling of hydraulic fractures in ductile shales for predicting the propagation pressure and fracture dimensions. The results are particularly interested for predicting the propagation of axial fractures in the horizontal direction and the confinement them in the vertical direction.
Keywords: Hydraulic Fracturing, Shale gas, Brittleness, Plasticity, Dislocation Theory, Mohr-Coulomb, net-pressure

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Technical Session 45 – California West
Petroleum Related Rock Mechanics 2

Wednesday, July 1, 2015, 04:00 pm - 05:30 pm

Chairs: Erling Fjaer & Janelle Homburg

ARMA 15-0362

Characterization of mechanical properties of rocks using numerical simulations and image analysis

Emilio A. Winograd[1], Sergio Bosco[1], Juan Pablo Alvarez[1], Marcos Mendoza A. [1], Damian Hryb[2], Martin Sanchez[1]
[1]Y-TEC, [2]YPF

Determining mechanical properties of reservoir rocks through mechanical testing is a well-established procedure. Static properties obtained from these tests (Young's modulus, Poisson's ratio, UCS, etc.) are fundamental to calibrate both 1D (well-scale), and complex 3D static and dynamic geomechanical models (reservoir-scale). These mechanical laboratory tests have the disadvantage of being destructive, making it impossible to obtain large amounts of data, limiting the generation of the geomechanical models of reservoirs. In this context, numerical simulations of laboratory tests can be a good alternative to obtain mechanical properties of rocks without performing expensive destructive tests.
In this paper, we present a methodology based on numerical simulations and image analysis (thin sections, micro-photographs and/or micro-tomographs of cores) to get mechanical properties from Brazilian tests simulations.

The methodology, consists on generating a model which reproduces mineralogy, texture and structure of the rock sample. Then, the Brazilean test simulation is performed, which outputs elastic and fracture properties of the sample. The obtained results were succesfully compared with mechanical tests in laboratory.

ARMA 15-0201

Numerical Modelling of Rock Mechanics Experiments as an Input for Coupled Hydromechanical Simulation

Antonio Claudio Soares[1], Flavia de Oliveira Lima Falcao[1], Melissa Cristina Duque Nogueira Kiewiet[1], Raquel Quadros Velloso[2], Eurípedes do Amaral Vargas Jr. [2], Leigh Hessel Kiewiet[3], Shane Kager[3]
[1]PETROBRAS/CENPES, [2]PUC-Rio/DEC, [3]CSIRO/ARRC

The main method to predict and manage petroleum reservoirs is numerical simulation in which, traditionally, the rock compressibility is the only geomechanical parameter taken into account. During exploitation, though, the reservoir-rock deforms, causing porosity and permeability variation, what cannot be represented by compressibility. Considering this, a more complete representation of the rock stress-strain behavior is a key point for any geomechanical numerical analysis. A good mechanical characterization of the rock based on rock mechanics and petrophysical lab experiments is a starting point, followed by the numerical calibration of the rock behavior observed in the laboratory. This last stage can be done *via* modelling of the experiments, aiming to define a constitutive model and the respective mechanical and elastic parameters that best represent the rock behavior. Within this context, a number of mechanical numerical modelling of rock mechanics experiments on different carbonate rocks have been conducted. Modified Drucker Prager and Modified Mohr Coulomb constitutive models have been adopted for the analyses, and different stress paths were considered – hydrostatic, compressive triaxial and edometric. Rock hydromechanical behavior has also been numerically assessed for some of the tested rocks, which allowed for the construction of a pseudocoupling table, that relates porepressure to porosity and permeability, horizontal and vertical, multipliers for different stress conditions. The resultant numerical stress – strain curves have shown in general a good fitting with the experimental ones. The mechanical and elastic parameters calibrated in this way, together with the multipliers table, can be taken to reservoir simulation for a pseudocoupled hydromechanical model. This coupling method is encouraged due to its good relation between computational cost and accuracy.

Keywords: constitutive model, rock mechanics experiments, coupling, reservoir simulation.

ARMA 15-0409

Static versus dynamic moduli: another piece in the puzzle

Erling Fjaer[1], Anna M. Stroisz[1], Rune M. Holt[1,2]
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Static and dynamic moduli of rocks may vary a lot, not only between different rock types, but also for a specific rock sample depending on the stress path and the stress level.
During unloading, the difference vanishes completely initially (in this dispersion-less rock), but picks up gradually as the load is further reduced. Subsequent reloading shows a similar pattern, with largely reduced difference between the static and dynamic moduli at the turning point, and gradual increase as the loading proceeds.
A semi-empirical model describing the relations between static and dynamic moduli during first loading, has previously been used successfully to establish a tool which predicts strength and static stiffness from wireline log data. It has also been shown how a simple model for the static:dynamic relation during unloading may be utilized to derive dispersion in the range from seismic to ultrasonic frequencies.
In this study the role of friction is investigated, using the model of Nihei et al. as a basis. The results support the assumption that frictional slip is the dominating process during unloading. The model is

calibrated by matching it to observations during unloading. The calibrated model is then used to subtract the effect of frictional slip from the static compliance during loading. The remaining difference from static to dynamic compliance, which may be associated with crushing of asperities in fractures or grain contacts, is found to behave largely as expected intuitively, thus supporting the assumption about its relevance. As this procedure allows us to observe the crushing process quantitatively, it enables us to derive a separate model description for it. This is a necessary step for the establishment of a complete constitutive model for the relations between static and dynamic moduli.

ARMA 15-0522

Influence of indexation and impact energy on bit/rock interface law in percussive drilling: an experimental study

Marion Fourmeau[1], Alexandre Depouhon[2], Alexandre Kane[1], Hieu Nguyen Hoang[1], Emmanuel Detournay[2]
[1]Sintef, [2]UoM

This paper presents the results of a laboratory study aimed at assessing the influence of indexation (the ratio of the bit angular velocity over the activation frequency) and impact energy (proportional to impact velocity squared) on the performance of percussive drilling (PD). This work is motivated by the recognition that despite numerous experimental and theoretical studies, the dependence of the penetration rate on indexation and impact energy remains poorly understood. A subsidiary issue that we address is the link between the penetration of the bit after each impact and the average penetration rate of the bit after multiple impacts. Indeed, chipping caused by the impact of the bit on the rock creates craters that are larger than the bit button marks (i.e. rock is fragmented and removed under and between the buttons [1]), with the consequence that the observed rate of penetration (ROP) obtained during PD is larger than what could have been inferred from the penetration obtained with a single impact test made in laboratory. This relationship between the bit ROP and the button penetration depends on the indexation between two percussive activations and presumably also on the impact energy. Understanding the relations between average bit ROP and single impact bit penetration, and quantifying the dependence of these relationships on indexation and impact energy will lead to the formulation of more realistic bit/rock interface laws that implicitly account for repeated impacts of the bit on the rock.

The experimental procedure underlying this study involves multiple sequential drop tests on a Kuru granite block, each followed by an indexation of the bit after cleaning of the debris. A rotating apparatus has been set up to allow a rotation of $\Delta\theta = 10°$ of the rock block between each impact. The impact force and the drill bit penetration are deduced from strain gauge measurements in the drop bar, and the bit velocity, measured at the initial contact point, enables the calculation of the impact energy. The force/penetration response, as well as the dissipated energy, representative of the bit/rock interaction can then be identified, as depicted in Figure 1.

After each impact, the impacted surface is cleaned of all the rock debris and the volume of removed rock is determined by comparing the successive rubber imprints of the rock face made after each impact, using a 3D stereo-lithographic volume reconstruction. This provides a direct input for the computation of the specific energy as well as a measure of the maximal penetration after cleaning, which is likely to differ from the results based on the strain gauge measurements after the cleaning operation. This study will thus make the link between the bit penetration for a single impact and the average ROP caused by multiple impacts, under idealized cleaning conditions. Moreover, by applying a very low impact energy, it will also provide data to assess the existence of an energy barrier, as was postulated in [2].

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[2] Depouhon A., Denoël V., Detournay E., 2013. A drifting impact oscillator with periodic impulsive loading: Application to percussive drilling. Physica D 258, 1-10.

ARMA 15-0584

A combined method to measure Biot's coefficient for rock

Xuejun Zhou[1], Alex Vachaparampil[1], Ahmad Ghassemi [1]
[1] *University of Oklahoma*

Biot's coefficient can be calculated by a few equations, including the following three: (1) $\alpha = 1 - K/K_s$, (2) $\alpha = (\partial\sigma/\partial p)_{\Delta\varepsilon_v=0}$, (3) $\alpha = \left(\Delta V_p/\Delta V_b\right)_{\Delta p=0}$, where K is bulk modulus of rock, K_s is grain bulk modulus of rock, σ is the confining stress, p is the pore pressure, ε_v is the volumetric strain, V_p is the pore volume and V_b is the rock bulk volume. Consequently, these equations represent three different approaches to measure this coefficient. We developed a combined method to measure Biot's coefficient by these three different approaches using a single laboratory setup. The methodology is to conduct a drained hydrostatic test to obtain the relationship between pore volume and rock bulk volume changes at different hydrostatic pressures at first, and then to adjust confining pressure and pore pressure to derive their correlation upon a constant volumetric strain condition, and then to measure the bulk modulus of the rock sample by conducting a drained hydrostatic test. The last step is to unify the pore pressure and confining pressure to simulate an unjacketed hydrostatic test to acquire the grain bulk modulus. This method requires accurate and direct strain measurement and a perfect saturation condition on the rock sample. This method allows us to acquire the Biot's coefficient for one rock sample by the three different equations at the comparable test conditions. A comparison of the results by these different approaches and a discussion on their pros and cons are also presented.

ARMA 15-0566

Acidizing of hollow cylinder chalk specimens and its impact on rock strength and wormhole network structure

Lars Erik Walle[1], Euripides Papamichos[1]
[1] *SINTEF Petroleum Research AS*

Injection of acid into limestones or chalk reservoirs may be a cost effective way to stimulate oil production. The acidizing process results in the formation of wormholes that may act as flow channels and therefore increase the near wellbore permeability of the formation. However, these wormholes may have unwanted side effects on formation integrity, especially for high depletion or drawdown.

We have recently reported results from a study of linear acidizing of oil and brine saturated 1.5" chalk plugs which subsequently underwent compaction tests to see the effect of the acidizing on the rock properties[1]. The hydrostatic compaction tests show wormhole collapse a few MPa below the onset of pore collapse, with a significantly larger pore-collapse pressure for oil-saturated samples as compared to saturation with brine. Comparison with measurements done on intact core plugs also indicate a reduction of pore-collapse pressure for the acidized plugs.

These results motivated us to study the impact of acidizing on chalk with a more realistic geometry and on a larger length scale. The experiments were carried out on hollow cylinder specimens of the Mons chalk, which is an outcrop chalk that is analogues to North Sea chalk reservoirs, with a length and outer diameter of 200 mm and a hole diameter between 20 and 40 mm. Wormholes were created by flooding the sample with 15% HCl radially from the borehole and outwards with injection rates between 10 and 50 ml/min. The flooding was stopped after acid breakthrough, or close to breakthrough, before the samples were CT-scanned to characterize the wormhole structure, as seen in Fig. 1. After plugging of any breakthrough holes with cement, the samples underwent drawdown and depletion type of tests with radial brine flow while recording external and borehole deformation. In this contribution we present how acid injection rate influences wormhole structure

and the impact of wormholes on the strength properties and solids production of hollow cylinder chalk specimens.
A. Bauer, L. E. Walle, J. Stenebråten and E. Papamichos, 47th US Rock Mechanics / Geomechanics Symposium, San Francisco, USA, June 2013, ARMA 13-534.

Technical Session 46 – California East
Uncertainty: Assessment and Quantification / Rock Properties

Wednesday, July 1, 2015, 04:00 pm - 05:30 pm

Chairs: John Harrison & anna maria ferrero

ARMA 15-0422

Using Image Windows for the Analysis of Fracture Traces and Fractures

Matthew Mauldon[1]
[1]*Virginia Tech*

Rock fractures are of considerable engineering significance in fields such as hard rock tunneling and fractured rock hydrology. Fracture traces – the 2d manifestations of fractures at exposed rock surfaces - can provide a wealth of information about the rock mass. Of particular interest is estimating statistical moments - e.g., the mean and variance of trace length - based on censored and biased field observations. This paper describes a novel and powerful approach to the interpretation of fracture trace data (that automatically corrects for sampling biases) , using what the author terms *image windows*. A window (sampling window) is a defined area on an exposed surface in which fracture traces can be observed and measured. Traces can intersect sampling windows in various ways; for example a trace can *transect* a sampling window, or a trace can be *contained* in a sampling window. We show how fields for contained, transecting, and one-end-in traces, can be constructed automatically using image windows, and how this information can be used to obtain information about trace length. A particular advantage of the method is that it can be applied in three dimensions, as well as two. We show how use of image windows in 3d can provide information about fracture size in the 3d rock mass.
Keywords: fracture traces, sampling bias, fracture size, 3d rock mass

ARMA 15-0543

Some open issues on the design of protection barriers against rockfall

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[1]*university of turin,* [2]*university of milan*

Risk is part of every sector of engineering design. It is a consequence of the uncertainties connected with the cognitive boundaries and with the natural variability of the relevant variables. In soil and rock engineering areas, in particular, uncertainties are linked to geometrical and mechanical aspects and the model used for the problem schematization. While the uncertainties due to the cognitive gaps could be filled by improving the quality of numerical codes and measuring instruments, nothing can be done to remove the randomness of natural variables, except defining their variability boundaries with stochastic studies. Probabilistic analyses represent a useful tool to run parametric analyses and to identify the more significant aspects of a given phenomenon: they can be used for a rational quantification and mitigation of risk. The connection between the cognitive level and the probability of failure is at the base of the determination of risk, which is often quantified through the assignment of safety factors. But these factors suffer from huge conceptual limits, which can be only overcome by adopting mathematical techniques with sound bases, not so used up to now (Einstein et al. 2010; Brown 2012). The present paper gives a description of the problems and the more reliable techniques used to quantify the uncertainties that characterize the large number of parameters that are involved in rock slope risk assessment, through the description of a real case specifically related to

rock fall. Limits of the existing approaches and future developments of the research are also evidenced.

Keywords: risk, uncertainty, probability, rock mass.

ARMA 15-0652

CHARACTERISTIC TRIAXIAL STRENGTH OF INTACT ROCK

Nezam Bozorgzadeh[1], John P. Harrison[1]
[1]University of Toronto

Current Limit State Design (or Load and Resistance Factor) codes and guides (e.g. EN-1997 (CEN, 2004) and Canadian Foundation Engineering Manual (CGS, 2006)) require determination of characteristic values of geotechnical parameters as a fundamental step in the design process.
Such design codes and manuals usually give general guidance on selecting the characteristic value. For example, EN-1997 requires the characteristic value of a geotechnical parameter to be selected as a *cautious estimate* of the value affecting the occurrence of the limit state. Furthermore, in the case of using statistical methods EN-1997 states that '*the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%*'. Unfortunately, there seems to be no consensus in the rock engineering community on the interpretation of such phrases, with the result that there is often confusion about the method to be used to identify characteristic values. This is particularly true for the characteristic triaxial strength of intact rock.
In this paper we will explore alternative possible approaches to determining the characteristic triaxial strength of intact rock. For the purpose of this analysis, an extensive published data set of triaxial strength of Ankara andesite (Sari, 2012) is used. In our analysis we fit the Hoek-Brown (HB) criterion to these data, and compare alternative methods of estimating a criterion that represents characteristic strength. The methods we use are i) calculating characteristic values of m and σ_c ; ii) reducing the fitted (mean) criterion by some proportion of the standard error of the fit; and iii) using quantile regression. Example curves using these methods are shown in Fig. 1. Additionally, in order to explore the effect of small numbers of strength test results (i.e. the common condition in rock engineering practice) we repeat the analysis on sub-samples of the original data and use the results of these analyses to draw conclusions regarding the reliability of estimates of characteristic strength.
The results of all these analyses are compared in the context of Limit State Design, and the appropriateness of their application discussed.

ARMA 15-0485

Measurements of fracture aperture in granite core using microfocus X-ray CT and fluid flow simulation

Kiyoshi Kishida[1], Tomohiro Ishikawa[1], Yosuke Higo[1], Atsushi Sawada[2], Hideaki Yasuhara[3]
[1]Kyoto University, [2]JAEA, [3]Ehime University

The authors have confirmed a change in the fracture flow under various long-term confining and thermal conditions. Consequently, through this change in the fracture flow, it had been thought that the structure of the fracture and the contact conditions on it were changed by the influence of the stress and the thermal conditions. However, no change in the fracture structure or in the contact conditions could be directly confirmed. In order to estimate the change in fracture aperture under various long-term confining and thermal conditions, measurements of the fracture aperture using microfocus X-ray CT are conducted. Through imaging data, the geometry of the fracture surface and the contact points are evaluated, and contact ratios of the fracture, the JRC and the aperture distribution are estimated. On the other hand, measurements using a laser scan profile sensor are also conducted and some parameters are estimated. In comparing these parameters, the validity of the X-ray CT data and an analysis of it will be discussed. In addition, a fracture flow simulation will be conducted using the geometry and the aperture data through the microfocus X-ray CT.

ARMA 15-0280

Estimation of Rock Strength by Means of Scratch Test

Ali Naeimipour[1], Jamal Rostami[1], Eric Keller[1], Omid Frough[2], Shugang Wang[2]

[1]Penn State University, [2]Pennsylvania State University

One of the main factors to perform a realistic stability analysis for underground spaces is having reasonably accurate estimate of the rock mass properties. This cannot be achieved without having enough geological information from the ground immediately surrounding the underground space. One of the major parameter in evaluating the condition of the rock mass is the intact rock strength. This parameter is usually estimated by testing the core drills in Geomechanics laboratories. A side from the fact that coring is an expensive/time consuming, preserving the in-situ condition of the core and preparation of the test samples are arduous/delicate tasks. On the other hand, although the well logging methods, majorly sonic logging, are in-situ, they are often operated in distantly spaced surface boreholes and provide extrapolated/low resolution information of the rock strength. It would be ideal if the strength of the rock could be estimated in-situ, and inside closely spaced boreholes drilled in the roof/ribs of the underground spaces. Estimation of the rock strength by scratching its surface has been shown to be successful with relatively high resolution. As a result, in this paper the results of initial tests ran for design of borehole scratcher probe are presented and explained. In this test series, different samples are scribed using disc cutters and drag bits with varied tip geometries. The initial tests are run on the soft/hard grout samples and will be continued by testing sedimentary rock samples with different ranges of strength. In rock samples, three rock blocks will be sandwiched together and casted by concrete in a rock box, Fig. 1. A triaxial load cell attached to the bit holder measures normal, rolling/tangential and side forces and the data is recorded by a data acquisition system on a computer. The position of the bit along the scratch is also simultaneously recorded. Fig. 2 shows the developed equipment. The samples are scratched at 15-20 mm spans to eliminate the effect of adjacent scratch(s). Depth of the scratches set to be 0.5 to 1.5 mm. Normal and rolling/tangential forces, as anticipated, are changing significantly during the tests and therefore are the major parameters in estimation of the rock/grout strength. Properties of grout and rock blocks are previously defined using Geomechanics tests, such as Uniaxial Compressive Strength, Point Load and Brazilian Tensile Strength. The results show a promising outcome for development of field borehole probe in the subsequent studies. The conceptual design of this instrument is also briefly discussed in this paper.

ARMA 15-0391

Measure of Friction during Drilling of Rocks

Mahendra Shewalla[1], John R. Smith[2], Radhey S. Sharma[3]

[1]URS Corporation, [2]Louisiana State University, [3]West Virginia University

Detournay and Tan (2002) performed experiments with a rock cutting device to measure the load required to fail the rock under confining stress. They proposed models describing the correlation between the specific energy and confining stress for shear dilatant rocks as a function of unconfined specific energy at failure, cutter rake angle (θ), internal friction angle (φ) of the rock, and an assumed interface friction angle (ψ) between the rock and the cutter. The aim of this paper is to evaluate the model proposed by Detournay and Tan (2002), which assumes that the interfacial friction angle between the rock and the cutter is equal to the internal friction angle. Quantitative assessment of rate of change coefficient (m) of specific energy was also accomplished to evaluate the assumption that m is constant for different bore hole pressures (p_m).

To evaluate the model, data on three (3) rock formations (Mancos Shale, Pierre Shale, and Catoosa Shale) was used in the study. The data on Mancos shale and Pierre shale was obtained from Zijsling (1987) and data on Catoosa Shale was obtained from Smith (1998). The results show that the interface friction angle varies with the bore hole pressure and is not equal to the internal friction

angle. The results also show that rate of change coefficient (m) of specific energy estimated using Detournay and Tan's proposed equation and an assumed internal friction is not representative of m obtained from known values of internal friction angle, interface friction angle, and back rake angle.

Equations

$$\psi = \tan^{-1}\left(\frac{F_y}{F_x}\right) - \theta \qquad (1)$$

Where F_y is the normal force component, F_x is the tangential force component, and θ is the back rake angle.

$$\varepsilon = \varepsilon_0 + m(\theta,\varphi,\psi)\, p_m \qquad (2)$$

ε is the specific energy required for cutting the rock, ε_0 denotes the specific energy under atmospheric conditions; p_m is the bore hole pressure (confining pressure), and m(θ,φ,ψ), is a function of cutter rake angle (θ) of the cutter, internal friction angle (φ) of the rock, and interface friction angle (ψ)

Technical Session 47 – Elizabethan AB
Wellbore and Drilling Mechanics 3

Wednesday, July 1, 2015, 04:00 pm - 05:30 pm

Chairs: Wu Zhang & Xinpu Shen

ARMA 15-0479

Testing Methods for Evaluating Drilling Fluid Effects on Gas Shale Stability

Quanxin Guo[1], Aaron Blue[1], James Friedheim[1]
[1] *Schlumberger*

The shale gas boom has been a game changer for the oil and gas industry. Shale gas development is ahead of science. Understanding of unconventional resources requires unconventional thinking and methods. Many drilling problems related to wellbore instability are caused by incompatibilities between the drilling fluids and the shale formations encountered. This problem is not new and the drilling industry has developed many effective testing methods for evaluating drilling fluids and shale compatibility. However, these useful methods, while effective for swelling shales, are not effective for unconventional resources, as unconventional shale is very differently from traditional swelling shale.

This paper presents why the traditional testing methods do not apply to unconventional shale. New testing methods were developed for evaluating drilling fluids effects on gas/oil shale. The newly developed testing methods include:
Fluid penetration test to evaluate drilling fluids penetration rate into the shale and sealing of micro-fractures in the fissile shale.
Indentation test to evaluate shale mechanical property degradation as a function of drilling fluids chemistry and rheology over time.
Scratch test to evaluate the depth of shale mechanics property degradation.
Wellbore stimulator to evaluate drilling fluids chemistry, rheology and filtration effects on shale and wellbore stability under downhole pressure and temperature, both on hole collapse and lost circulation evaluations.

Test results on Marcellus shale and other gas/oil shales will be presented to illustrate the effectiveness and usefulness for evaluating drilling fluids effects on unconventional shale and wellbore stability.

ARMA 15-0097

Integrated 1-D Workflow for Pore-Pressure Prediction and Mud-Weight Window Calculation for Subsalt Well Sections

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The aim of this work is to present an integrated workflow for the one-dimensional (1-D) analysis of pore-pressure (PP) prediction and mud-weight window (MWW) for sub-salt well sections as well as high-angle inclined well sections.
In this integrated workflow, empirical information, such as measured data and records of drilling events from offset wells, plays an essential role in the prediction of PP and MWW at the target well, along with a set of theoretical equations. The major steps in the workflow include the following: 1) With given data from a set of offset wells and a given location for a target well, prediction analysis of PP and MWW are performed with logging data and various measured data from offset wells first. These calculations and calibrations with known data from offset wells generate the values of model parameters for this field, and, thus, the results are empirical. These empirical values of model parameters will be used for subsequent calculations of PP and MWW at target well locations. 2) The tops-table method which performs depth-shift calculations is used for extrapolating/interpolating gamma ray and sonic logging data from offset wells to the target well location. 3) With logging data generated using the tops-table method and the empirical model data, PP and MWW can be obtained at the target well location.
A practical case using the workflow introduced here is also presented. This case is from an oilfield in deepwater Gulf of Mexico.

Logging data from three offset wells is provided for the calculation of PP and the design of MWW at the location of a given target well in a Gulf of Mexico field. Input data from offset wells include: gama ray, resistivity, and sonic data, along with information from drilling events and a series of measured data.

Resultant PP and MWW for the target well are illustrated in Figure 1, along with the values of PP and MWW from the three offset wells. It is shown that the resultant PP solution, PP_def, of offset wells has a significant deviation from its curves of theoretical value but is close to the empirical information. This indicates that (1) logging data is essential but not enough for an accurate prediction of PP and MWW for subsalt wells; and (2) the process of empirically calibration on model parameters with drilling events and measured data are essential for an accurate solution of PP and MWW. Therefore, this 1-D workflow is semi-analytical and semi-empirical.

This work presents a practical 1-D workflow for the prediction of PP and MWW for subsalt wells. With a practical case from Gulf of Mexico, it is illustrated that this 1-D workflow is semi-analytical and semi-empirical.

Keywords: Pore pressure, wellbore stability, mud weight window, fracture gradient, shear failure gradient.

ARMA 15-0310

Probabilistic Time-Dependent Thermo-chemo-poroelastic Borehole Stability Analysis in Shale Formations

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The importance of an accurate geomechanical model and borehole stability assessment is increasing in the petroleum industry due to the growth in the number of drilling operations in unconventional reservoirs. A large number of field developments are occurring in shale formations as a novel source of energy. Many of these reservoirs are thin layered, naturally fractured and high clay bearing; the presence of clay minerals in particular, make their mechanical behavior to be anisotropic and also make the rocks to become chemically active with the drilling fluid. Thus, wellbore stability analysis is crucial and challenging; In addition a good understanding of elastic and physiochemical properties of the formation would be necessary for better field development plans and to avoid future financial losses.
For this study elastic, petrophysical and physicochemical properties of the shaly Bakken Formation were tested and reported from a several number of core plugs in different wells drilled in the Williston basin, North Dakota. We measured various poro-mechanical (Young's modulus Poisson's ratio, Biot's coefficient), petrophysical (permeability and porosity), physiochemical (clay mineralogy, thermal diffusivity, membrane efficiency, thermal expansion coefficient) properties of Bakken shale along with the chemical properties of the drilling mud. The direction and the magnitude of the horizontal principal stresses were measured in the field with the data acquired from advanced logging tools in several wells. All of these values are coupled and used as input parameters in a time-dependent poroelastic constitutive model to calculate in-situ stresses and pore-pressure variations around the borehole. Changes in radial and hoop stresses were also plotted in the vicinity of the well. In the next step the model was run under Mohr-Columb failure criterion while including anisotropy in mechanical properties to evaluate the deformations and failure occurrences around the borehole. Finally probabilistic risk assessment was carried out to understand the sensitivity of the results to the uncertainties in the input parameters.

ARMA 15-0345

Effect of Rheology on Drilling Mud Loss in a Natural Fracture

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Effect of rheology on drilling mud loss in a single natural fracture is investigated in this work. In general, drilling mud may be treated as a single-phase incompressible fluid displaying non-Newtonian rheological characteristics such as yield stress and shear thinning. Loss of the drilling mud in the natural fracture is driven by the pressure drop between the wellbore and the reservoir. For a complex fluid with yield stress, when the pressure gradient falls below a threshold, mud invasion ceases and the fracture is considered sealed. Nevertheless, since the pressure gradient near the wellbore is the largest at the onset of drilling mud invasion and decreases as the mud flows further into the fracture, the rheology governing the fluid flow behaviors at the early time is the high shear rate rheology. In other words, the high shear rate rheology could play a critical role in controlling the rate of mud loss at the early time.

The Herschel-Bulkley model with a yield stress and power law for shear thinning has been commonly used to describe the drilling mud rheology. Since it is not uncommon that the drilling mud rheology exhibits a Newtonian plateau or even shear thickening in the high shear rate range (shear rate ~1000 1/s), a piecewise rheological model, modified based on the Herschel-Bulkley model, is employed to take into account the high shear rate rheology. A mathematical model is constructed by assuming the fracture geometry to be radial and that the natural fracture can be initially closed or open with an initial aperture. The mechanical deformation of the fracture is governed by local elasticity. Fluid flow inside the fracture is assumed to be in a steady state and can be approximated by the lubrication equation. The reservoir formation is permeable with the leak off following Carter's model. The problem defined above is solved numerically using an explicit moving mesh algorithm. Sensitivity analysis on the effects of the parameters, in particular, the rheological parameters and the leak off coefficient, is performed.

Circulation loss is a major problem while drilling through naturally fractured reservoirs. Quantitative prediction of the drilling mud loss is therefore critically needed for the control of lost circulation. The numerical analysis in this work provides a robust tool that allows not only systematic investigation of the effects of the formation and the fluid characteristics on the drilling mud loss, but also assessment for the improvement in the fluid design to control lost circulation.

ARMA 15-0341

Filter cake behavior during leakage at the cement-rock interface in wellbores

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Choices made during drilling can influence the quality of the cement sheath, and thus zonal isolation and well integrity. A number of parameters can affect zonal isolation: geomechanics, fluid and cement properties, and procedures used during drilling. The combination of field experience and research has improved the quality of zonal isolation in wells used for petroleum exploitation. However, the requirements of wells penetrating CO_2 storage reservoirs might be different – as temperatures, pressures and the downhole chemical environment will be dissimilar. It is important to understand the unique zonal isolation requirements of CO_2 wells to assure optimization of safety and cost-efficiency in Carbon Capture and Storage (CCS) projects. This was the aim of the experimental study presented in this paper.
Our approach was to prepare a set of cement-rock samples using different rocks and cements with varying types of drilling fluids at the interface. Any heterogeneity at the cement-rock interface was thereafter digitalized for each sample using X-ray μ-Computed Tomography (μ-CT). Special focus was directed towards mapping the geometry, size and extent of potential leakage paths – and how drilling fluid and filter cake covered the interface. Further, CO_2 leakage through the samples was measured using an in-house core flooding set-up, and the samples were re-scanned using μ-CT to map how they were affected by CO_2.
The 3D visualization after μ-CT scanning revealed potential leakage paths of complex geometry along the cement-rock interfaces of most samples. The percentage of rock-cement bonding was seen to clearly decrease with increasing presence of drilling fluid/filter cake. The core flooding experiments showed a correlation between the dimensions of interface micro-annuli and measured CO_2 flow. However, unpredictable fluid migration was also observed – underlining the importance of understanding how the non-solid/semi-solid drilling fluid and filter cake behave when subjected to downhole pressures. An analysis of this topic was performed in parallel with the experimental work.
In order to have a solid risk assessment of CCS operations, one must assure that procedures for ensuring well integrity are updated for CO_2 storage wells. Our work shows that the placement of annular and plug cement to ensure long-term zonal isolation is still a difficult task, and that modeling with ideal assumptions on leakage path shape and properties should be avoided.

ARMA 15-0708

Optimizing Drilling Parameters: A Preliminary Model--Drilling Carthage Mable

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This work reports an attempt at predicting optimized drilling parameters through modeling the relationships of mechanical specific energy (MSE) and rate of penetration (ROP) with key drilling parameters, including both weight on bit (WOB) and rotation rate of the drill bit per minute (RPM). Empirical equations were developed based on experimental data obtained from a TerraTek drilling simulator. The data processed includes the variation in the values of MSE; ROP; Torque, as function of WOB; RPM; hydraulic power; type of oil-based drilling fluids; and type of drill bit while drilling Carthage Mable. Teale's equation is expanded to express the MSE as a direct function of WOB and RPM only, while torque and depth of cut are represented as an intermediate function bridging them. Based on these equations, combinations of WOB and RPM values are determined, which lead to higher ROP for the use of lower MSE. Showing the potential benefit of drilling parameter optimization, the results are encouraging when compared to what was achieved in drilling experiments with operating parameters not optimized.

Technical Session 48 – Elizabethan CD
Fracture Mechanics 2

Wednesday, July 1, 2015, 04:00 pm - 05:30 pm

Chairs: Yanhui Han & Charles Collins

ARMA 15-0550

Modeling dynamic stimulation of geological resources

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Dynamic loading methods promise new modes for stimulating geological resources. In contrast to traditional fracturing methods (e.g. hydraulic fracturing) the stresses in the source region may be significantly larger than the insitu stress which helps creating fractures not oriented with the maximum insitu stress.
This paper discuss simulation of dynamic fracture initiation and propagation using Lawrence Livermore's GEODYN-L code. GEODYN-L is a massively-parallel multi-material Lagrangian code developed for shock wave propagation in heavily jointed rock masses. It has been validated by modeling various underground explosions over the years. Rock joints can be modeled in GEODYN-L both as embedded discontinuities as well as cohesive contacts.
Recently fluid elements have been added to model fluid flow caused by high explosive products expanding into the joints and cracks. We focus on various mechanisms of dynamic fracture generation in a rock formation with pre-existing joints/cracks. Various source geometries and energy release rates are considered to optimize the enhancement of the fracture network which could be stimulated later using traditional methods.

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ARMA 15-0719

Interpretations of Fracture Initiation and Orientations In a

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Multiple hydraulic fractures are postulated to initiated in a horizontal well during staged fracturing completion. This process is calculated based on a plane strain assumption and a fracture can be initiated when the tangential stress near the wellbore exceed the tensile strength. A 3D finite element calculations indicate the critical fracturing location may not be in the middle of the packed section postulated, instead this critical stressing region can be located in the near packer region and not along the transverse or longitudinal directions. This situation can directly impair our evaluation on increasing productivity or EUR over fracturing spacing. More over, for situations longitudinal fractures are possible, plastic yielding can initiate before an induced hydraulic fracture initiation, which either force the fracture to be in an unexpected locations. A combined 3D finite element method and simplified poroelastic model is used to analyze the stresses near a packed horizontal well and oriented perforations. The critical stress and the corresponding wellbore pressure for fracturing is generated including the fracturing orientations.

Staged fracturing strategy has been widely used in U.S. And Canada for tight formations including shale gas and oil production. Fractures or fracture network may be initiated from an open hole or perforations. Depending on the layout of the horizontal well, the perforation orientations, cluster of perforation, the distance to the packers in each stage, and a fracture network or fractures initiation

are of great interests for productivity. We normally calculate the tangential stresses near a wellbore and each perforation for open hole and cased hole, respectively. Whether a transverse or radial fracture can be generated, if a fracture can be initiated at a specific perforation, or a fracture can be initiated from the middle or at the edge of the packers remain unanswered. These issues must be addressed by considering the critical stresses at the wellbore and perforations once we shall have a clear pictures if plastic yield occurs prior fracturing, or which perforation is oriented at an optimum position referring to the in-situ stress, and if the near packer regions are heavily influenced by the in-situ stresses. A combined 3D finite element model and analytical poro-elastoplastic model is developed to analyze effective stresses focusing on near packer regions, near oriented perforations and evaluating the plasticity and stresses near a wellbore in order to determine where, at what fracturing pressures and locations a fracture can be initiated in a horizontal wellbore, including fracturing blocking mechanism due to plasticity.

We conclude:
Tangential stress reduction trend can be reversed if plasticity occurs near wellbore so that a tensile fracturing is in question.
A fracturing may initiate at one of the perforation where the local tangential stress is minimum and the second or other fractures can initiate afterward if the fracturing pressure can increase further in a cased well
A fracture is likely to initiate from the packer which may change our predicted fracture spacing.
A combination of the stresses comparisons between the near a packer and middle regions where a plane strain condition may be applicable, fracturing pressure calculations near perforations at different orientations, and tangential stresses near a wellbore/perforations before and after plasticity are the keys to determine the location of a fracture and the surface fracturing pressure interpretations.
Those breakdown pressures observed on the surface must be interpreted based on those near packers stresses, possible plasticity, perforation orientation and the corresponding stresses so that we may determine an optimum stage, cluster spacing and corresponding fracturing spacing and ultimate productivity.
Title: Interpretations of Fracture Initiation and Orientations during Staged Horizontal-Well Fracturing in Tight Formations

ARMA 15-0068

Experimental study of fracture initiation and propagation from a wellbore

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Hydraulic fracturing is widely used in petroleum industry to create a high conductivity pathway between the reservoir and well. However, the initiation and propagation of fracture in the near wellbore region will fundamentally influence the development of fractures, and finally the treatments of hydraulic fracturing. Thus, the identification of fracture path during the hydraulic fracturing has a significant help to improve its understandings. Most previous experiments in the laboratory to observe the fracture evolution are conducted in a block of rock using tracer material, and the fractures will initiate and propagate inside it. The observation approaches include the acoustic emission (AE), and/or simply the block opening. However, they both have limitations. AE locations involve a measurement error, especially for a block. For the block opening, it has a high risk to damage the hydraulic fracture, and indeed, some fractures may not be observed due to the human factors.
In this work, a new experiment is designed to observe the fracture initiation and propagation directly in a rock plate. It is actually a cavity expansion test with two symmetric pre-cracks, as shown in Fig. 1a. The rock plate is under plane strain condition with an unknown out-of-plane loading as the intermediate stress. The confining pressures are used to simulate the influences of in-situ stresses, and the pre-cracks are for perforations. A specially-designed device can apply the pressure on the

boundary of the center hole, which creates a tensile loading on the pre-cracks and initiates their propagation. It needs to note that the influences of fluid are not considered in the experiments, due to the limit of plate size and difficulties of sealing issues. An experimental result is shown in Fig. 1b, and it was under the confining pressures 2MPa and 4MPa respectively. The perforation angle was 30 degree between pre-cracks and the maximum in-situ stress. It can be observed that the fractures (crack # 1 and 3 as shown in Fig. 1b) initiated and propagated from the pre-cracks and switched to the orientation of maximum in-situ stress. Two additional cracks (crack # 2, 4) were also identified to initiate from the boundary of hole, which may be the consequences of the stress concentrations on the boundary.

ARMA 15-0222

Boundary element analysis of non-planar three-dimensional cracks using complex variables

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This paper reports new developments on the complex variables boundary element approach for solving three-dimensional problems of cracks in elastic media. These developments include implementation of higher order polynomial approximations and more efficient analytical techniques for evaluation of integrals. The approach employs planar triangular boundary elements and is based on the integral representations written in a local coordinate system of an element. In-plane components of the fields involved in the representations are separated and arranged in certain complex combinations. The Cauchy-Pompeiu formula is used to reduce the integrals over the element to those over its contour and evaluate the latter integrals analytically. The system of linear algebraic equations to find the unknown boundary displacement discontinuities is set up via collocation. Several illustrative numerical examples involving a single (penny-shaped) crack and multiple (semi-cylindrical) cracks are presented.

ARMA 15-0291

Coupled geomechanics and fluid flow computational algorithm for modeling hydraulic fracturing with pre-existing natural fractures in unconventional shale reservoirs

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The fracturing technologies used for horizontal wells are experiencing continuous improvements, aiming at achieving high commercial production from tight and unconventional oil and gas reservoirs. As these technologies become more complicated and expensive, it is quite mandatory to accompany them by an appropriate computational simulation, which can provide a cost-effective methodology for better optimizing the fracturing workflow while minimizing risks. By virtue, fracturing processes encapsulate multi-physics systems led by the tightly coupled geomechanics and fluid dynamics. Due to complexity, numerical stability and reliability it poses major challenges. The geomechanics model describes deformation and stress distributions of rock formations, and calculates fracture propagation under injected fluid pressure conditions, while fluid flow behavior inside opened fractures is derived from the fluid dynamics model in domains whose geometries are determined by rock deformation. This paper proposes a two-dimensional time-dependent and tightly coupled computational algorithm for hydraulic fracturing simulations. This algorithm intimately and locally couples a fluid dynamics and a geomechanics model while providing fracture propagation criteria. It uses the Cubic law model for computing the fluid flow in opened fractures and fluid volume caged inside the fractures. Finite Element Method (FEM) is used to evaluate stresses and deformation of elastic rock blocks. Lagrange Multipliers method is used to prevent the penetration during contact between adjacent rock blocks while imposing the fracture tip displacements constraint conditions. The propagation criterion of hydraulically induced fractures is imposed by the displacement correlation method. This scheme is also coupled with tensile and shear-failure models to describe natural fracture evolution and its interaction with approaching hydraulically induced fractures. The geomechanics and fluid dynamics common components naturally lead to a tightly coupling integrative system, where its unknowns are rock block corner displacements, the Lagrange Multipliers in case blocks are in contact or displacement constraints are applied, and the fluid's pressure at junctions of opened fractures. The proposed algorithm solves for all unknowns simultaneously and in a tightly coupled manner while the general Newton algorithm is implemented for solving the overall nonlinear system of equations at each time step. By using this algorithm, fracture interaction, intersection and offsetting by pre-existing natural fractures are studied. The results clearly demonstrate the significant impact of the distribution of pre-existing natural fractures on the main fracture propagation path and communication between multiple injection points along a horizontal wellbore. The numerical results provide insight for understanding how hydraulically induced fractures interact with pre-existing natural fractures and form complex fracture networks.

ARMA 15-0073

A New Stacked Height Growth Model for Hydraulic Fracturing Simulation.

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The rapid development of shale resources in the past decade has brought a focus on the process of hydraulic fracturing. Shale reservoirs tend to be characterized by a complex 3D stress field and vertically heterogeneous mechanical properties, which have always been challenging for hydraulic fracturing modeling and particularly for properly predicting the shape of an induced fracture. Current state-of-the-art simulators use two distinct approaches. The first one, referred to as planar 3D model (PL3D), is based on the boundary element method, in which the fracture is assumed to be a plane and its entire footprint is discretized into elements. The equations governing fluid flow, elasticity, and mass balance are solved numerically, coupled with the fracture propagation rules. This approach is very accurate but also very CPU intensive. The second approach is based on pseudo-3D (P3D) model, which separately considers the vertical growth and horizontal propagation of the fractures. In this approach, the width profile and fracture height are calculated based solely on the local pressure and local vertical stress profile. This approach is less CPU intensive, but relies on several assumptions including the fracture being initiated and its leading front propagating in the lower stress layer compared to the neighboring layers above and below. If this is not the case, the fracture height growth can become unstable, since it is not directly correlated to the global fracture mass balance like for the planar 3D model, and can lead to significant inaccuracy in the predicted fracture height growth.

In this paper, we present a new model as an enhancement of the pseudo-3D model. Instead of just one row of elements connected along the horizontal direction as in the P3D model, the model consists of multiple rows of elements vertically stacked and connected. For each row of elements, the assumption of the fracture front being in the lower stress layer is satisfied locally. This model accounts for vertical flow between elements of different rows to better model the path of least resistance for the fracturing fluid. Similar to the pseudo-3D model, the width profile and stress intensity factor at the top and bottom of the fracture depend not only on the local stress profile, but also on the pressure profile along the stack of elements. This model predicts the fracture height more accurately than the pseudo-3D model, without sacrificing CPU time, and gives results close to the ones from the full planar 3D model.

This paper first presents the theoretical background behind this model, followed by comparisons and validation against a planar 3D model and a pseudo-3D model for biwing hydraulic fractures. This stacked height model is implemented in an unconventional fracture model that simulates complex fracture networks due to interactions of hydraulic fractures with natural fractures and accounts for stress shadow effect. A case study illustrates how a more accurate prediction of fracture height can impact the overall shape of complex fracture networks and, ultimately, the production through an integrated fracturing-to-production simulation workflow.

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