SPONSORS

Asheville 2009 is the 43rd U.S. Rock Mechanics Symposium and the 4th U.S.-Canada Rock Mechanics Symposium. The symposium is sponsored by the American Rock Mechanics Association, a professional society that serves as the direct link in the United States to the professionals, firms, teachers, and students in the fields of rock mechanics and rock engineering.

Asheville 2009 is organized in conjunction with the Canadian Rock Mechanics Association, the umbrella organization serving the rock mechanics professionals from the Canadian Institute of Mining and the Canadian Geotechnical Society.

The following companies have generously provided support for Asheville 2009:

Advantek International

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WELCOME

Welcome to Asheville and the Blue Ridge Mountains!

Known as an art colony, a healing resort, and a home to notable statesmen, Asheville is one of the most welcoming, vibrant cities in America. Asheville has been heralded as a prime arts destination by the New York Times and features hundreds of fine artists, performing arts venues, mountain crafters, folk artists, hip arts neighborhoods, numerous art galleries and myriad art events. Finally, America's most visited National Park, Great Smoky Mountains, is nearby as is the scenic Blue Ridge Parkway.

This symposium encompasses all aspects of rock mechanics, rock engineering, and geomechanics. Included are scientific and engineering papers addressing geology and geophysics, civil, mining, petroleum, and underground construction applications. The symposium especially aims to focus on fundamentals that are of common interest to all disciplines.

The symposium would not have been possible without the efforts of the authors, the Technical Committee Co-Chairs (Rico Ramos, John Kemeny, and Jon Olson), the Organizing Committee, and especially Peter Smeallie, the Executive Director of ARMA. Many thanks to all of you!

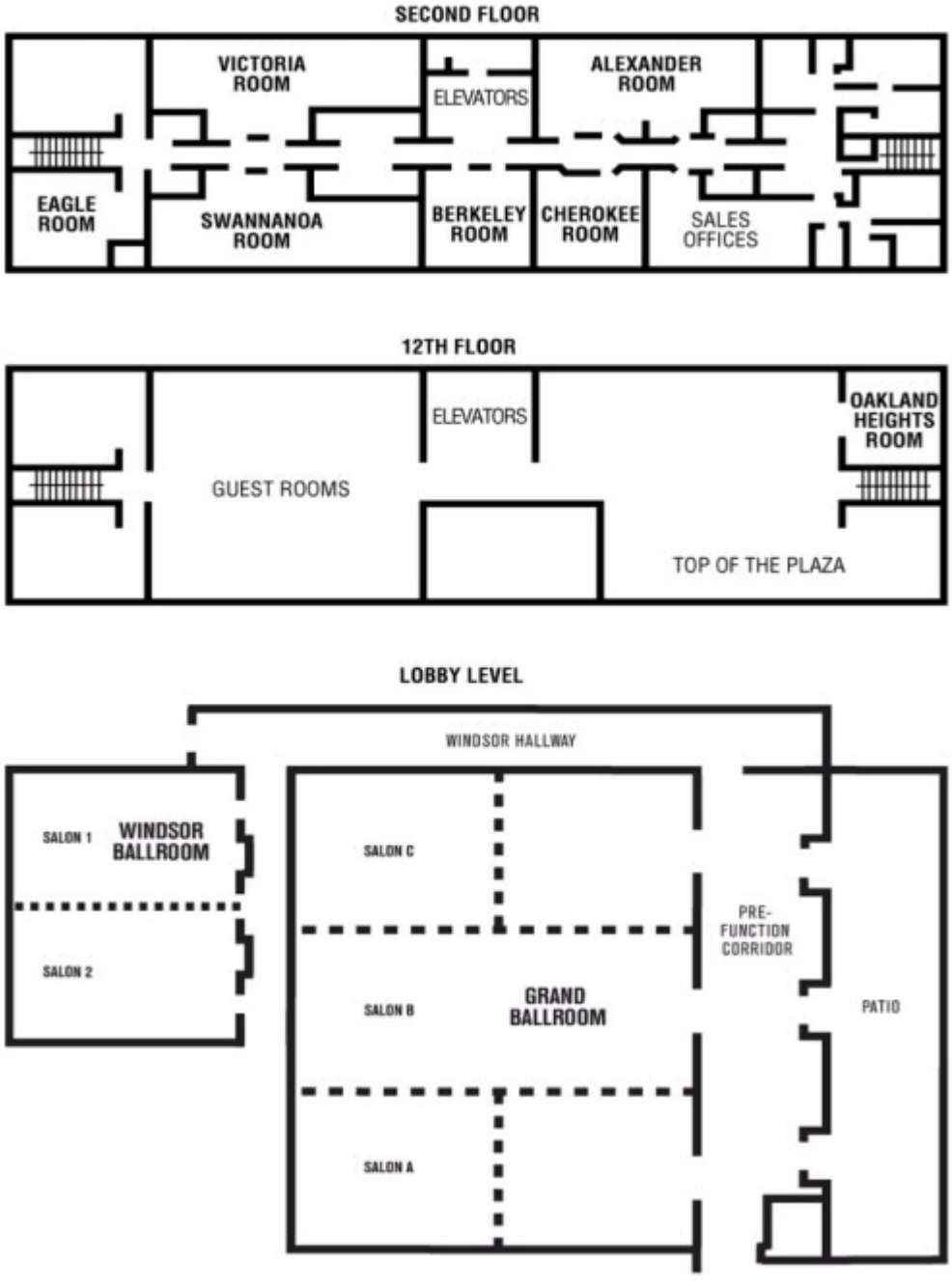
My sincere hope is that the interactions with colleagues at the Symposium and the information found in these proceedings will have a significant impact on you this year and throughout your career.

Best Regards,

Erik Westman, Symposium Chair

HOTEL MEETING ROOMS

For more hotel information, please visit the Marriott's website:
www.marriott.com/hotels/event-planning/floor-plans/avlbr-renaissance-asheville-hotel/



ACKNOWLEDGEMENTS

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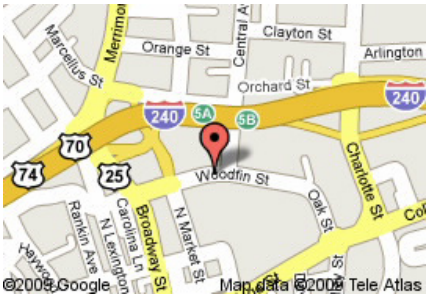
ARMA BOARD OF DIRECTORS

GENERAL INFORMATION

Maps/Parking

Downtown Asheville is easy to navigate by car or foot. Local maps are contained in the delegate bag and are available at the front desk. Free parking is available at the hotel.



Registration

On-site registration is available on the first floor Prefunction Corridor during the following hours:

Sunday, June 28th: 7:00am – 9:00pm
Monday, June 29th: 10:15am – 3:45pm
Tuesday, June 30th: 10:15am – 4:45pm
Wednesday, July 1st: 7:00am – 3:15pm

Exhibit Hall Hours

The exhibit hall is located in the Grand Ballroom. The hours are:

Sunday, June 28th: 7:00pm – 9:00pm
Monday, June 29th: 10:15am – 3:45pm
Tuesday, June 30th: 10:15am – 4:45pm
Wednesday, July 1st: 10:15am – 1:15pm

Speaker's Breakfast

All speakers and session chairs are required to attend the speaker's breakfast from 7:00am–7:50am in the Top of the Plaza (12th floor) on the day of their oral presentation. Tables will be identified by session number and speakers will load their presentations via a portable USB storage device to the session laptop.

Speaker Ready Room

The speaker ready room is located behind the registration desk in the hotel Prefunction Corridor on the first floor. A laptop and LCD will be available.

Monday, June 29th: 7:00am – 5:30pm
Tuesday, June 30th: 7:00am – 4:45pm
Wednesday, July 1st: 7:00am – 3:15pm

EXHIBITORS

Booth # 1
MTS Systems Corp.
14000 Technology Drive
Eden Prairie, MN 55344

Researchers worldwide turn to MTS for the technology and expertise they need to accurately and efficiently determine the physical characteristics of rock and concrete materials for research, industrial and commercial applications. The MTS offering includes high-performance servohydraulic load frames, durable test accessories, versatile digital controllers and fully-featured test application software.

Booth # 2
ADAM Technology
Suite 3
41 Belmont Avenue
Belmont, WA, 6104
Australia

ADAM 3DM Analyst software has been used for Open pit surveying and Geotechnical mapping. With the addition of autonomous Unmanned Aerial Vehicles to ADAM's product range, low-cost and quick-turnaround aerial mapping is now a reality, and the 3DM Analyst Underground Mapping Field Kit extends the functionality of the software to Underground applications as well.

Booth # 3
Geokon, Inc.
48 Spencer Street
Lebanon, NH 03766

Geokon, Inc. manufactures a full range of high-quality geotechnical instrumentation suitable for monitoring the safety and stability of a variety of civil and mining structures including dams, tunnels, foundations, mine openings, piles, etc. Geokon's product line includes piezometers, pressure cells, strain gages, inclinometers, load cells, extensometers, settlement systems, dataloggers, etc.

Booth # 4
Rocscience Inc.
31 Balsam Avenue
Toronto, Ontario M4E 3B5
Canada

Rocscience offers easy-to-use analysis and design software for geotechnical applications. Created by experienced engineer-developers, our high-quality programs enable users to save time and money when analyzing and designing solutions in rock and soil. All Rocscience software is backed by free technical support and a 30-day money back guarantee.

Booth # 5
Weatherford Laboratories
8845 Fallbrook Drive
Houston, TX 77064

Weatherford Laboratories' Rock Mechanics Lab provides core-based testing and engineering analysis services for applications to hydraulic fracture design, wellbore stability, sand production, and other reservoir engineering and geophysical applications. The laboratory testing currently offers comprehensive strength test with ultrasonic velocities, pore volume compressibility test, long-term creep test, Brazilian tensile test, Mohr-Coulomb failure analysis, thick-wall cylinder test and multi-stage compressive test.

Booth # 6
MALA GeoScience USA, Inc.
2040 Savage Road
Charleston, SC 29416

MALA GeoScience USA, Inc. is the North American distributor 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.

Booth # 7
The Academy of Geo-Professionals
1801 Alexander Bell Drive
Reston, VA 20191

AGP was founded in October 2008 by practicing geo-professionals who were members of the American Society of Civil Engineers' Geo-Institute. The Academy was created primarily to offer a voluntary, post-license credential that provides professional engineers an opportunity to gain further recognition in the broad field of geotechnical engineering.

Booth # 8
AEG: Association of Engineering and Environmental Geologists
PO Box 460518
Denver, CO 80246

AEG is the acknowledged international leader in environmental and engineering geology, and is greatly respected for its stewardship of the profession. AEG offers information on environmental and engineering geology useful to practitioners, scientists, students, and the public. Other geosciences organizations recognize the value of using and sharing AEG's outstanding resources.

Booth # 10
Engineering Seismology Group
1 Hyperion Court
Kingston, Ontario K7K 7G3
CANADA

ESG designs, manufactures, installs and supports microseismic monitoring systems and provides real-time monitoring, processing and analysis services to clients who want better information and improved decision-making capabilities. Operators can use this information to increase workplace safety, reduce operating or environmental risk, and optimize production techniques.

EXHIBITORS

Booth # 11
Geocomp Corporation/GeoTesting Express, Inc.
1145 Massachusetts Avenue
Boxborough, MA 01719

Geocomp helps clients identify, manage and mitigate risk with these services: Active Risk Management, TMActive Risk Monitoring, Structural Health Monitoring, Underground Engineering, Value Engineering, Forensic Engineering, and Claims Consultation. GeoTesting Express provides the fastest turnaround time available for high-quality laboratory testing services of soil, rock and geosynthetics.

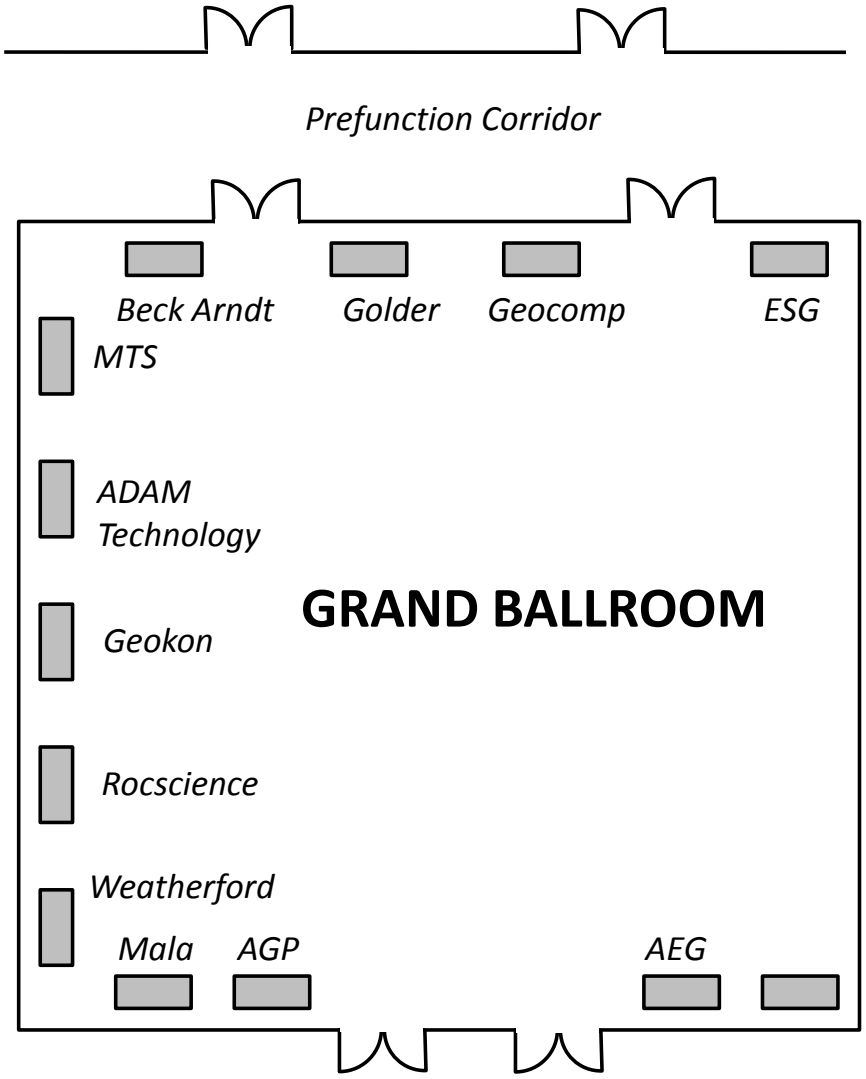
Booth # 12
Golder Associates, Inc.
18300 NE Union Hill Road
Redmond, WA 98052

Golder Associates is a leading international geo-engineering consulting firm, offering geomechanics, hydrodynamics, geologic, and geophysical service including site characterization, planning and permitting, engineering, and development. Golder Associates provides services to the oil and gas, mining, transportation, and environmental industries. Golder Associates' FracMan Technology Group is a recognized leader in analysis and engineering of fractured reservoirs, rock slopes, underground mines, tunnels, geothermal and Carbon Capture and Storage (CCS).

Booth # 13
Beck Arndt Engineering Pty. Ltd.
9 Reid Drive
Chatswood West, NSW, 2067
Australia

Beck Arndt Engineering Pty. Ltd. specializes in engineering and numerical analysis for the mining, oil and gas, aerospace and automotive industries. We have expertise in rock mechanics, fracture mechanics, seismology, multi-physics simulation and large-scale three-dimensional, non-linear numerical modelling and are a leading provider of non-linear numerical modelling services to the mining industry.

Exhibitor's Floor Plan



SYMPOSIUM PROGRAM

FRIDAY, JUNE 26

Special Activity
Joint Dinner Meeting of the Carolinas Section of AEG and the Western Branch, North Carolina Section of ASCE with Mark Molinari, President AEG, *featured speaker*
Asiana Grand Buffet, Asheville — 6:00 pm – 9:00 pm

SUNDAY, JUNE 28

Registration — Prefunction Corridor ..... 7:00 am – 9:00 pm
Exhibits Open — Grand Ballroom ..... 7:00 pm – 9:00 pm

ARMA Board Meeting

Oakland Heights Room ..... 8:00 am – 4:00 pm

Exhibit Set Up

Grand Ballroom ..... 2:00 pm – 5:00 pm

Short Courses

ANALYSIS & DESIGN OF FOUNDATIONS ON AND IN ROCK, Fred Kulhawy

Alexander ..... 8:00 am – 5:00 pm

Workshop

NUMERICAL MODELING FOR UNDERGROUND MINE EXCAVATION DESIGN, *sponsored by* NIOSH

Windsor A ..... 8:00 am – 4:00 pm

Opening Remarks

Ballroom Salon C ..... 6:00 pm – 7:00 pm

Erik Westman, Chair, Asheville 2009

President, ARMA

Mark Molinari, President, AEG

SUNDAY, JUNE 28

MTS Invited Lecture
Introduction, Gregg Pence, MTS Systems Corp.

GEOMECHANICS THROUGH THE ALCHEMIST'S PRISM: COMPLEX PROCESS COUPLINGS RELATED TO DEEP GEOLOGIC SEQUESTRATION AND ENERGY RECOVERY, Derek Elsworth

SYNOPSIS: Fluids in the shallow crust exert important controls on a wide spectrum of natural and engineered phenomena. The complex interaction of stress and particularly that of chemistry exhibit important feedbacks which influence the evolution of the mechanical and transport properties of rocks. These feedbacks in turn relate crucially to the subsurface recovery of hydrocarbons from the full spectrum of conventional through unconventional reservoirs, to the recovery of hydrothermal and non-hydrothermal geothermal resources, to the secure and enduring sequestration of energy by-products, and to the earthquake cycle, for example. Enigmatic interactions between stress and chemistry in mediating the evolution of permeability and strength in natural and engineered systems are explored – as relevant to high-carbon through low-carbon economies. Examples are selected to illustrate the significance of these interactions in controlling the response of hydrocarbon and geothermal reservoirs, fracture treatments, radioactive waste disposal and in the response of faults.

BIO: Derek Elsworth is a Professor of Energy and Geo-Environmental Engineering at Penn State with 25 years of teaching, research and consulting experience in computational mechanics, flow and transport in fractured media and rock mechanics. This work is focused broadly on complex physiochemical interactions of reservoir geomechanics and to the safe sequestration of energy byproducts. He served as ARMA treasurer (2000-2004) and chaired the 2001 US Symposium on Rock Mechanics. He is the founding chair of the graduate programs in Geo-Environmental Engineering and in Energy and Geo-Environmental Engineering and co-developer of an international exchange program in Energy and Environment (ICEEIT) between universities in Europe and the United States. He is the co-founder of the Center for Geomechanics, Geofluids and Geohazards (G3) at Penn State, a center for multidisciplinary studies in rock and fluid physics.

His recent research interests have focused on understanding the role of fluids on natural and engineered processes in the Earth's crust, particularly in the evolution of transport and mechanical properties of fractured rocks under the complex action of stress, fluid pressures and chemistry. This work has elevated the state-of-science in the deep geological sequestration of radioactive wastes and of CO2, mining, petroleum and geothermal engineering and of volcanic hazards.

Ballroom Salon C ..... 6:00 pm – 7:00 pm

Opening Reception and Exhibits

Sponsored by MTS Systems Corp.

Grand Ballroom ..... 7:00 pm – 9:00 pm

MONDAY, JUNE 29

Speaker's Breakfast	Top of the Plaza	7:00 am – 7:50 am
Registration	Prefunction Corridor	7:00 am – 5:30 pm
Speakers Ready Room	Prefunction Corridor	7:00 am – 5:30 pm
Exhibits Open	Grand Ballroom	10:15 am – 3:45 pm

Keynote:

ROCK MECHANICS/GEOMECHANICS FROM AN ENERGY PERSPECTIVE,
Sid Green, ARMA Fellow, Schlumberger

Ballroom Salon C ..... 8:00 am - 8:45 am

MONDAY, JUNE 29

TECHNICAL PRESENTATIONS

Session 1: Numerical Modeling of Discontinuous Media

Windsor A ..... 9:00 am – 10:00 am

Each presentation is 15 minutes

Chairs: Matthew Mauldon & Ronald Yeung

9:00 THREE-DIMENSIONAL DISCONTINUOUS DEFORMATION ANALYSIS (3-D DDA) WITH NTH-ORDER POLYNOMIAL DISPLACEMENT FUNCTIONS (5), M. Ronald Yeung

9:15 MODELING VARIATION OF STRESS AND PERMEABILITY IN NATURALLY FRACTURED RESERVOIRS USING DISPLACEMENT DISCONTINUITY METHOD (47), Qingfeng Tao

9:30 COUPLED THERMAL/FRACTURING PROCESS OF ROCKS (65), Baotang Shen

9:45 THERMO-POROELASTIC FINITE ELEMENT ANALYSIS OF ROCK DEFORMATION AND DAMAGE (121), Sang Hoon Lee

Session 2: Underground Support Design

Windsor B ..... 9:00 am – 10:15 am

Each presentation is 15 minutes

Chairs: Anthony Spearing & Jeramy Decker

9:00 STRESS CORROSION OF ROCKBOLTS IN AUSTRALIAN COAL MINES (182), Peter Craig

9:15 INVESTIGATION OF THIN SPRAY-ON LINERS USING NUMERICAL MODELING (4), Rudrajit Mitra

9:30 GEOLOGIC EVALUATION, ROOF STABILITY ANALYSES, AND GROUND SUPPORT DESIGN FOR UNDERGROUND MINE SLOPE ENTRIES (93), Kevin J. Ma

9:45 THE APPLICATION OF A STRUCTURAL THIN SUPPORT LINER (TSL) ON MINES (32), Anthony (Sam) JS Spearing

10:00 WORKING SAFELY UNDER INVERSE RAISE BOREHOLES AT BRUNSWICK MINE (203), Jean Garant

COFFEE BREAK

Sponsored by Advantek International

Exhibits Open

Grand Ballroom ..... 10:15 am – 10:45 am

Commercial Mini-Session: Rocscience, Inc.

Ballroom Salon C ..... 10:30 am – 10:45 am

TECHNICAL PRESENTATIONS

Session 3: Borehole Geomechanics And Drilling I

Windsor A ..... 10:45 am - 12:00 noon

Each presentation is 15 minutes

Chairs: Kray Luxbacher & Azra Tutuncu

10:45 A STRAIN-SOFTENING MODEL FOR DRILLING-INDUCED DAMAGE ON BOREHOLES IN WILLISTON BASIN (26), Zane Zeng

11:00 ROCK MECHANICAL MODELLING FOR A UNDERBALANCED DRILLING RATE OF PENETRATION PREDICTION (97), Farid Shirkavand

11:15 CASING INTEGRITY IN HYDRATE BEARING SEDIMENTS (138), Reem Freij-Ayoub

MONDAY, JUNE 29

11:30 THE MECHANISM OF ROTATION OF CONICAL BIT (27), Eunhye Kim

11:45 STRENGTHENING A WELLBORE WITH MULTIPLE FRACTURES: FURTHER INVESTIGATION OF FACTORS FOR STRENGTHENING A WELLBORE (67), Hong Max Wang

Session 4: Natural Discontinuities — Characterization and Modeling

Windsor B.....10:45 am – 12:15 pm

Each presentation is 15 minutes

Chairs: Ahmad Ghassemi & Don Banks

10:45 SEISMIC WAVE PROPAGATION IN FRACTURED CARBONATE ROCK (68), Weiwei Li

11:00 APPLICATION OF SYNTHETIC ROCK MASS MODELING TO ESTIMATE THE STRENGTH OF JOINTED SANDSTONE (59), Glenn Sharrock

11:15 A NUMERICAL INVESTIGATION OF SCALE EFFECTS ON THE BEHAVIOR OF DISCONTINUOUS ROCK (145), David Alexander Beck

11:30 ANISOTROPY OF THE STRENGTH, DEFORMABILITY, AND DILATANCY OF ROCK FRACTURES (54), Pooyan Asadollahi

11:45 THREE-DIMENSIONAL POROELASTIC DISPLACEMENT DISCONTINUITY SIMULATION OF NATURAL FRACTURES (154), Ahmad Ghassemi

12:00 A COMPUTATIONAL STUDY: THE SCALING RELATIONSHIP BETWEEN FLUID FLOW AND DISPLACEMENT IN SINGLE FRACTURES (144), Christopher Lee Petrovitch

LUNCH

Sponsored by Hess Corporation

Exhibits Open

Grand Ballroom.....12:15 pm – 1:40 pm

ARMA General Meeting

Grand Ballroom.....1:40 pm – 2:00 pm

TECHNICAL PRESENTATIONS

Session 5: Carbon Sequestration - Flow and Mechanical Processes

Windsor A.....2:00 pm – 3:15 pm

Each presentation is 15 minutes

Chairs: Derek Ellsworth & Lee Chin

2:00 COUPLED HYDROMECHANICAL AND REACTIVE TRANSPORT PROCESSES WITH APPLICATION TO CARBON SEQUESTRATION (17), Scott Johnson

2:15 HYDRAULIC FRACTURING MECHANISMS IN CARBON SEQUESTRATION APPLICATIONS (30), Scott Johnson

2:30 INVESTIGATION OF CO2 INJECTION INDUCED COAL-GAS INTERACTIONS (99), Zhongwei Chen

2:45 DUAL POROELASTIC RESPONSE OF COAL SEAM TO CO2 INJECTION (164), Yu Wu

3:00 LABORATORY TESTING ON GEOMECHANICAL PROPERTIES OF CARBONATE ROCKS FOR CO2 SEQUESTRATION (11), Xuejun Zhou

MONDAY, JUNE 29

Session 6: Lidar and Remote Sensing for Rock Mass Characterization I

Windsor B .....2:00 pm – 3:15 pm

Each presentation is 15 minutes

Chairs: John Kemeny & James Donovan

2:00 THE USE OF TERRESTRIAL LIDAR IN DETERMINING DIRECTIONAL JOINT DILATION ANGLE VALUES (98), Clay Mansfield

2:15 ANALYZING LIDAR DATA FOR ROCK MASS CHARACTERIZATION USING A FAST AND SIMPLE MESH-LESS TECHNIQUE (123), Matthew Mauldon

2:30 INTEGRATING GIS-BASED GEOLOGIC MAPPING, LIDAR-BASED LINEAMENT ANALYSIS AND SITE SPECIFIC ROCK SLOPE DATA TO DELINEATE A ZONE OF EXISTING AND POTENTIAL ROCK SLOPE INSTABILITY LOCATED ALONG THE GRANDFATHER MOUNTAIN WINDOW, LINVILLE FALLS SHEAR ZONE CONTACT, SOUTHERN APPALACHIAN MOUNTAINS, WATUGA COUNTY, NORTH CAROLINA (181), Kenneth A. Gillon

2:45 STATISTICAL CHARACTERIZATION OF ROCK STRUCTURE USING LIDAR (155), Michael Edward Levy

3:00 A COMPARISON OF PHOTOGRAMMETRY AND LASER SCANNING FOR THE PURPOSE OF AUTOMATED ROCK MASS CHARACTERIZATION (122), James Donovan

COFFEE BREAK
Sponsored by Golder Associates

Exhibits Open

Grand Ballroom .....3:15 pm – 3:45

Commercial Mini-Session: Beck Arndt Engineering Pty. Ltd

Ballroom Salon C .....3:30 pm – 3:45 pm

Bicker and Beer: A Debate between Maurice Dusseault and Jean Claude Roegiers

What have we learned over the past 50 years and why is it important?

Sponsored by Advantek International

Ballroom Salon C .....4:00 pm – 5:00 pm

ASCE Rock Mechanics Committee

Room 1202.....5:00 pm – 6:00 pm

Special Activity:

AN EVENING AT THE TAYLOR RANCH

Assemble in Lobby.....6:00 pm - 9:00 pm

TUESDAY, JUNE 30

Speaker's Breakfast	Top of the Plaza	7:00 am – 7:50 am
Registration	Prefunction Corridor.....	7:00 am – 5:30 pm
Speakers Ready Room	Prefunction Corridor.....	7:00 am – 5:30 pm
Exhibits Open	Grand Ballroom.....	10:15 am – 4:45 pm

KEYNOTE
GEOLOGY AND GEOHAZARDS IN WESTERN NORTH CAROLINA, Rick Wooten, Senior Geologist, N.C.Department of the Environment and Natural Resources

Ballroom Salon C .....8:00 am – 8:45 am

TUESDAY, JUNE 30

TECHNICAL PRESENTATIONS

Session 7: Fragmentation, Excavation and Caving

Windsor A.....9:00 am – 10:15 am

Each presentation is 15 minutes

Chairs: GS Esterhuizen & Steven Brandon

9:00 DISCRETE ELEMENT MODELING OF IMPACT FRAGMENTATION IN ROCK FALL ANALYSIS (153), Yuannian Wang

9:15 CALIBRATION OF 3D CUTTER-ROCK MODEL WITH SINGLE CUTTER TESTS (160), Ihsan Berk Tulu

9:30 DISTURBED FLOW IN BLOCK CAVING (70), Glenn Sharrock

9:45 EXTENT OF DAMAGE ASSOCIATED WITH THE PASSAGE OF THE COMPRESSIVE STRESS WAVE GENERATED BY BLASTING (92), Jeffrey Craig Johnson

10:00 EFFECT OF SEAM DIP ON FACE ORIENTATION OF LONGWALL TOP COAL CAVING (110), Quang Hong Dao

Session 8: Borehole Geomechanics and Drilling II

Windsor B.....9:00 am – 10:15 am

Each presentation is 15 minutes

Chairs: John McLennan & Ahmed Abou-Sayed

9:00 DRILLABILITY OF A ROCK IN TERMS OF ITS PHYSICO-MECHANICAL AND MICRO-STRUCTURAL PROPERTIES (40), Umesh Prasad

9:15 CHANGING SHALE STRENGTHS WITH INVERT EMULSION DRILLING FLUIDS: THEORY AND MEASUREMENT (170), Terry Hemphill

9:30 BOREHOLE STABILITY SIMULATIONS OF AN HPHT FIELD USING ANISOTROPIC SHALE MODELING (185), Ole Kristian Søreide

9:45 BOREHOLE FAILURE RELATED TO BEDDING PLANE (106), Andang Kustamsi

10:00 WELLBORE STABILITY AND BREAKDOWN PRESSURE IN HETEROGENEOUS, ANISOTROPIC FORMATIONS, Roberto Suarez-Rivera

Coffee Break
Sponsored by Advantek International

Exhibits Open

Grand Ballroom.....10:15 am – 10:45 am

Commercial Mini-Session: TerraTek, A Schlumberger Company

Ballroom Salon C.....10:30 am – 10:45 am

TECHNICAL PRESENTATIONS

Session 9: Lab Characterization: Flow and Dynamics

Windsor A.....10:45 am – 12:00 noon

Each presentation is 15 minutes

Chairs: Ion Ispas & Roberto Suarez-Rivera

10:45 CHARACTERIZING INTERNAL MACROPORES USING CROSS-SPECIMEN ACOUSTIC TOMOGRAPHY: VERIFICATION OF TWO DIMENSIONAL RESULTS (45), Mary MacLaughlin

11:00 MECHANICAL PROPERTIES OF HIGH AND LOWER POROSITY OUTCROP CHALK AT VARIOUS WETTING STATES (139), Bizhan Zangiabadi

TUESDAY, JUNE 30

11:15 PERMEABILITY CHANGES DUE TO SHEAR DILATANCY IN UNCEMENTED SANDS (157), Jon Olson
11:30 EVOLUTION OF SHEAR STRENGTH AND PERMEABILITY DURING SHEAR-HOLDING IN A SIMULATED ROCK FRACTURE UNDER MODERATE STRESS AND ROOM TEMPERATURE CONDITION (150), Yuta Kawaguchi
11:45 MEASURING STATIC AND DYNAMIC MODULI AS FUNCTION OF STRESS FOR A WEAK SANDSTONE (179), Jørn F. Stenebråten

Session10: Rock Mass Characterization I: Slope Stability, Design and Analysis

Windsor B.....10:45 am – 12:00 noon

Each presentation is 15 minutes

Chairs: Rebecca Latham & Reginald Hammah

10:45 A NEW METHOD FOR THREE-DIMENSIONAL SLOPE STABILITY ANALYSIS—THE VECTOR SUM ANALYSIS METHOD (85), Ming-wei Guo
11:00 PROBABILISTIC SLOPE ANALYSIS WITH THE FINITE ELEMENT METHOD (149), Reginald Hammah
11:15 IN SITU LARGE SIZE NON CONVENTIONAL SHEAR TESTS FOR THE MECHANICAL CHARACTERIZATION OF A BIMROCK IN THE SANTA BARBARA OPEN PIT MINE (Italy) (184), Niccolo' Coli
11:30 IS THERMAL FATIGUE A POSSIBLE MECHANISM FOR FAILURES OF SOME ROCK SLOPES IN RIO DE JANEIRO, BRAZIL? (126), E. A Vargas, Jr.
11:45 DETECTION OF FRACTURE IN ROCKS USING ACOUSTIC EMISSION MONITORING, Roberto Suarez-Rivera

LUNCH

Sponsored by TerraTek, A Schlumberger Company

Exhibits Open
Grand Ballroom.....12:00 noon – 1:15 pm

NATIONAL ENERGY TECHNOLOGY LABORATORY'S EXTREME DRILLING LAB, William J. Ayers, P.E.

Grand Ballroom..... 12:50 pm – 1:15 pm

TECHNICAL PRESENTATIONS

Session11: Lab Characterization of Mechanical Response: Creep and Poro-Mechanics

Windsor A.....1:15 pm – 2:45 pm

Each presentation is 15 minutes

Chair: David Yale

1:15 STRENGTH AND FAILURE MODE AS A FUNCTION OF MACROPORE SPACING: EXPERIMENTAL AND NUMERICAL INVESTIGATION (44), Mary MacLaughlin
1:30 EXPERIMENTAL STUDY OF DISSOLVING EFFECT ON MECHANICAL CHARACTERISTICS OF ROCK SALT (28), Tang Yanchun
1:45 ADVANCES IN RESEARCHES OF THE MECHANICAL BEHAVIORS OF DEEP BEDDED SALT ROCKS IN CHINA (95), Yinping Li

TUESDAY, JUNE 30

2:00 UNDRAINED POROELASTIC RESPONSE OF BEREA SANDSTONE AND INDIANA LIMESTONE TO CONFINING AND DEVIATORIC STRESS CHANGE (43), Babak Akbarnejad

2:15 EXPERIMENTAL INVESTIGATION OF THE EFFECTIVE STRESS COEFFICIENT FOR VARIOUS HIGH POROSITY OUTCROP CHALKS (118), Edvard Omdal

2:30 RESEARCH ON INFLUENCING FACTORS AND CHARACTERISTICS EXPERIMENTATION OF RHEOLOGICAL PARAMETERS OF SOFT-SOIL UNDER STEADY LOADING (136), Hu Hua

Session12: Rock Mass Characterization II: Dams and High-Walls

Windsor B .....1:15 pm - 2:30 pm

Each presentation is 15 minutes

Chairs: Mary MacLaughlin & Bill Gates

1:15 EVALUATING ROCK MASS DEFORMABILITY CHARACTERISTICS USING RIGID PLATE LOAD TEST IN BAKHTIARY DAM (74), Amirreza Ghasemi

1:30 LATERALLY CONTROLLED SHEAR TESTING OF 1:200 SCALE MODEL GRAVITY DAM MONOLITHS OVER A FOUNDATION WITH THREE-DIMENSIONAL INTERFACIAL ROUGHNESS (83), Dom Galic

1:45 STUDY ON THE DEFORMATION RESPONSE OF A WATER INLET HIGH ROCK SLOPE EXCAVATION IN A LARGE HYDROELECTRIC STATION IN SOUTHWEST OF CHINA (72), Jiliang Zhu

2:00 FOUNDATION INVESTIGATIONS FOR REFURBISHMENT CUT-OFF WALLS AT ARAPUNI DAM, NEW ZEALAND (50), Stuart Read

2:15 REPAIR OF THE PI'ILANI/HANA ARCHES, PI'ILANI HIGHWAY, MAUI, HAWAII (101), William Chester Gates

COFFEE BREAK

Sponsored by Golder Associates

Exhibits Open

Grand Ballroom .....2:45 pm – 3:15 pm

TECHNICAL PRESENTATIONS

Session13: Underground Geomechanics Modeling

Windsor A ..... 3:15 pm - 4:45 pm

Each presentation is 15 minutes

Chairs: Sarah Wilson & Hani Mitri

3:15 EFFECT OF STOPE UNDERCUTTING ON ITS WALL OVERBREAK (200), Hani Mitri

3:30 3-DIMENSIONAL NUMERICAL MODELLING OF STOPE SEQUENCING FOR MINE PLANNING (202), Hani Mitri

3:45 UTILIZING CONVERGENCE READING TO DETERMINE STABILITY AND SUPPORT CATEGORY IN NATM TUNNELING AT THE DEVIL'S SLIDE TUNNEL (137), Jeramy Bruyn Decker

4:00 HYDROMECHANICAL EVOLUTION AND SELF-SEALING OF DAMAGE ZONES AROUND A MICROTUNNEL IN A CLAYSTONE FORMATION OF THE SWISS JURA MOUNTAINS (152), George William Lanyon

TUESDAY, JUNE 30

4:15 STUDY ON APPLICATION OF DISPLACEMENT MEASUREMENT METHOD IN 3-D PHYSICAL MODEL TESTS OF CAVERN COMPLEX (14), Weishen Zhu

4:30 LAMODEL ANALYSIS OF THE CRANDALL CANYON MINE COLLAPSE (61), Keith A. Heasley

Session14: Constitutive Models of Rock Deformation

Windsor B ..... 3:15 pm - 4:30 pm

Each presentation is 15 minutes

Chairs: Paul Lapointe & Neal Nagel

3:15 HYDROMECHANCIS OF A VIRTUAL ROCK CORE (35), Jishan Liu

3:30 DAMAGE RHEOLOGICAL MODEL WITH NON-STATIONARY PARAMETERS AND ITS ENGINEERING APPLICATION (111), Qiangyong Zhang

3:45 PHYSICAL AND NUMERICAL INVESTIGATION OF A CEMENTED GRANULAR ASSEMBLY UNDER UNIAXIAL AND TRIAXIAL COMPRESSION (24), Mian Sohail Akram

4:00 ANHYDRITE BEHAVIOR IN A SALT FORMATION: WIPP APPLICATIONS (81), Byoung Yoon Park

4:15 RELIABILITY ASSESSMENT OF HOEK-BROWN ROCK MASS STABILITY (21), Wenxi Fu

AWARDS RECEPTION AND BANQUET
Grand Ballroom ..... 7:00 pm – 9:30 pm

WEDNESDAY, JULY 1

Speaker's Breakfast	Top of the Plaza	7:00 am – 7:50 am
Registration	Prefunction Corridor	7:00 am – 3:15 pm
Speakers Ready Room	Prefunction Corridor	7:00 am – 3:15 pm
Exhibits Open	Grand Ballroom	10:15 am – 1:15 pm

KEYNOTE:
ARMA Fellows Panel, WHAT DOES THE FUTURE HOLD FOR ROCK MECHANICS?
Ballroom Salon C ..... 8:00 am – 8:45 am

TECHNICAL PRESENTATIONS

Session 15: Fluid-Coupled Mechanisms and Transport

Windsor A ..... 9:00 am - 10:15 am

Each presentation is 15 minutes

Chairs: Larry Murdoch & John McLennan

9:00 MODELING FLUID MIXTURE TRANSPORT AND CROSS-FLOW IN LAYERED MEDIA (33), Mao Bai

9:15 WATER IMBIBITION IN OILFIELD ROCKS AND APPLICATIONS TO OIL RECOVERY (156), Martin Suarez

9:30 ANALYSIS OF HYDROMECHANICAL WELL TESTS IN FRACTURED SEDIMENTARY ROCK AT THE NAWC SITE, NEW JERSEY (201), Larry Murdoch

9:45 MODELING METHANE EMISSIONS AND VENTILATION NEEDS BY EXAMINATION OF MINING INDUCED PERMEABILITY CHANGES AND RELATED DAMAGE TO VENTILATION CONTROLS (146), Kray Luxbacher

10:00 ROCK-FLUID INTERACTION: RECENT OBSERVATIONS OF CHEMO-MECHANICAL EFFECTS, John McLennan

WEDNESDAY, JULY 1

Session 16: In Situ Stress Measurement Techniques

Windsor B ..... 9:00 am – 10:00 am

Each presentation is 15 minutes

Chairs: Keith Heasley & Tae Young Ko

9:00 PRECISE MINIMUM HORIZONTAL STRESS DETERMINATION FROM PUMP-IN/FLOWBACK TESTS WITH DRILLING MUD (88), Torunn Beathe Gederaas

9:15 CRITICAL REVIEW OF LEAK-OFF TEST AS A PRACTICE FOR DETERMINATION OF IN-SITU STRESSES (3), Gang Li

9:30 DEVELOPMENT OF ROCK STRESS MEASUREMENT PROBE BASED ON THE PILOT HOLE WALL DEFORMATION METHOD AND LABORATORY TESTS (131), Ki-Ha Lee

9:45 EVALUATING THE PRESENT IN-SITU STRESS-STATE FOR THE RICHTON, MS, STRATEGIC PETROLEUM RESERVE SITE USING GEOMECHANICAL ANALYSES (76), Jose G. (Lupe) Arguello Jr.

COFFEE BREAK

Sponsored by Advantek International

Exhibits Open

Grand Ballroom ..... 10:15 am – 10:45 am

TECHNICAL PRESENTATIONS

Session 17: Rock Mass Characterization III: Classification, Deformation, and Monitoring

Windsor A ..... 10:45 am – 12:00 noon

Each presentation is 15 minutes

Chairs: Erik Westman & Rebecca Latham

10:45 ROCK SLOPE STABILITY ANALYSIS ALONG THE NORTH CAROLINA SECTION OF THE BLUE RIDGE PARKWAY: USING A GIS TO INTEGRATE SITE DATA AND DIGITAL GEOLOGIC MAP (171), Rebecca Latham

11:00 METAMORPHIC ROCK MASS CHARACTERIZATION USING THE GEOLOGICAL STRENGTH INDEX (GSI) (19), Miguel Truzman

11:15 APPLICATION OF REAL TIME MONITORING SYSTEM IN CUT SLOPE MANAGEMENT SYSTEM OF KOREA (114), Jeong Yeob Lee

11:30 MONITORING AND COMPUTATIONS ON A LANDSLIDE IN AN OPEN PIT MINE (103), Masantonio Cravero

11:45 DOUBLE-DIFFERENCE TOMOGRAPHY FOR MONITORING UNDERGROUND STRESS REDISTRIBUTION, Erik Westman

Session 18: Fracture Initiation and Growth-Mixing Up the Modes

Windsor B ..... 10:45 am – 12:00 noon

Each presentation is 15 minutes

Chairs: Jon Olson & James Donovan

10:45 ANALYSIS OF THE KII MODE SHEAR FRACTURE TOUGHNESS FOR BRITTLE MATERIALS (56), SJ Jung

11:00 EXPERIMENTAL AND THEORETICAL STUDY OF MIXED-MODE I+III CRACK PROPAGATION AND SEGMENTATION (142), Ruiting Wu

11:15 SOME STATISTICAL ASPECTS OF CONSTANT STRESS-RATE TESTING FOR SUBCRITICAL CRACK GROWTH (96), Taeyoung Ko

11:30 OBSERVATION, CHARACTERIZATION AND MODELING OF FRACTURE INITIATION IN ROCK (63), Alexander Chudnovsky

11:45 EFFECT OF THERMAL SHOCK AND RAPID UNLOADING ON MECHANICAL ROCK PROPERTIES (84), Kwangmin Kim

WEDNESDAY, JULY 1

LUNCH (on your own)
Exhibits Open
Grand Ballroom.....12:00 noon – 1:15 pm
Exhibit Take Down
Grand Ballroom.....1:15 pm – 2:45 pm

TECHNICAL PRESENTATIONS

Session19: Rock Mass Characterization IV: Index Tests and Correlations

Windsor A.....1:15 pm – 2:45 pm

Each presentation is 15 minutes

Chairs: Robert Zimmerman & Teri Nichols

1:15 THE EFFECT OF STYLUS HARDNESS AND SOME TEST PARAMETERS ON CERCHAR ABRASITIVITY INDEX (191), Paul Hagan

1:30 SHEAR STRENGTH AND DAMAGE ZONES OF BEDDING PLANES IN MARTINSBURG SHALE (130), Matthew Mauldon

1:45 GEOTECHNICAL CHARACTERIZATION OF SEVIER AND ROME SHALE, EAST TENNESSEE (94), Arpita Nandi

2:00 RELATIONSHIPS BETWEEN INDEX AND PHYSICAL PROPERTIES OF WEATHERED OCALA LIMESTONE (105), Nick Hudyma

2:15 QUALITY CONTROL OF TURKISH CALCAREOUS NATURAL STONE (6), Ali Sariisik

2:30 A NEW FORECAST METHOD OF OPENING DISPLACEMENT AND ITS ENGINEERING APPLICATION (16), Xiaojing Li

Session 20: Induced Fracturing - Exotic Modes - Out of the Ordinary

Windsor B.....1:15 pm – 2:45 pm

Each presentation is 15 minutes

Chairs: Jing Du & Ivan Gil

1:15 THE DISTINCT ELEMENT ANALYSIS FOR HYDRAULIC FRACTURING CONSIDERING THE FLUID VISCOSITY (37), Hiroyuki Shimizu

1:30 POROELASTIC ANALYSIS OF HYDRAULIC FRACTURE PROPAGATION (129), Wenxu Xue

1:45 MULTI-FRACTURE COMPLEXITIES IN DRILLING WASTE INJECTION: WAGON-WHEEL UNIFORM DISPOSAL DOMAIN OR SECONDARY FRACTURE BRANCHING (119), Lujun (Lou) Ji

2:00 FRACTURE-CONDUCTIVITY LOSS CAUSED BY GEOCHEMICAL INTERACTIONS BETWEEN MAN-MADE PROPPANTS AND FORMATIONS (12), Jim D. Weaver

2:15 AN EVALUATION OF THE EFFECTS OF FRACTURE DIAGENESIS ON FRACTURE TREATMENTS: MODELED RESPONSE (104), Dae Sung Lee

2:30 TILT MONITORING OF HYDRAULIC FRACTURE PRECONDITIONING TREATMENTS (100), Zuorong Chen

COFFEE BREAK
Patio ..... 2:45 pm – 3:15 pm

TECHNICAL PRESENTATIONS

Session 21: Reservoir Geomechanics - From Bitumen to Granite

Windsor A.....3:15 pm – 4:30 pm

Each presentation is 15 minutes

Chairs: Rico Ramos & Sidney Green

WEDNESDAY, JULY 1

3:15 A $100MM "ROCK": BITUMEN IN THE DEEPWATER GULF OF MEXICO (10), Gang Han

3:30 A FULLY-COUPLED FINITE ELEMENT CODE FOR MODELING THERMO-HYDRO-MECHANICAL PROCESSES IN POROUS GEOLOGICAL MEDIA (120), Robert W. Zimmerman

3:45 ASPECTS OF COUPLING BETWEEN PETROLEUM RESERVOIR FLOW AND GEOMECHANICS (89), David Tran

4:00 SURFACE DEFORMATION-BASED RESERVOIR MONITORING IN INHOMOGENEOUS MEDIA (49), Jing Du

4:15 EVOLUTION OF FRACTURE PERMEABILITY IN GRANITE AND ITS EVALUATION VIA COUPLED CHEMO-MECHANO CONCEPTUAL MODEL (13), Hideaki Yasuhara

Session 22: Lidar and Remote Sensing for Rock Mass Characterization II

Windsor B.....3:15 pm - 4:15 pm

Each presentation is 15 minutes

Chairs: John Kemeny & Erik Westman

3:15 THE MEASUREMENT AND MONITORING OF COAL MINE SUBSIDENCE USING INTERFEROMETRIC APERTURE RADAR (125), James Donovan

3:30 ESTIMATING THE EXTENT OF THE DISTURBED ROCK ZONE AROUND A WIPP DISPOSAL ROOM (82), Courtney Herrick

3:45 ATTENUATION ANALYSIS OF SURFACE WAVES USED TO LOCATE SHALLOW MANMADE TUNNELS (143), Niklas Henry Putnam

4:00 NON-CONTACT DETECTION OF ACOUSTIC EMISSION SIGNALS FROM ROCK SURFACES (141), Xiaoqing Sun

CLOSING SESSION

Grand Ballroom.....4:30 pm – 4:45 pm

Special Activity

"Til Beth Do Us Part," a theatrical comedy

Asheville Community Theatre (across from hotel patio).....8:00 pm

THURSDAY, JULY 2

Short Course

MEASUREMENT AND QUANTIFICATION OF JOINT ROUGHNESS AND APERTURE, P.H.S.W. Kulatilake

Alexander.....8:00 am – 5:00 pm

FIELD TRIPS

Blue Ridge Parkway Rock Slope Stability and Scenery

Assemble in Lobby.....9:00 am – 5:00 pm

Gorges State Park

Assemble in Lobby.....9:00 am – 5:00 pm

INSIDE ASHEVILLE

Three local Asheville connoisseurs have kindly provided an inside look into Asheville and many of its offerings. Thanks to Rick Wooten, Merri and Will McLean for taking the time to compile this guide.

For current events, www.exploreasheville.com is an excellent quick resource, particularly "Happenings" and "Discover Downtown."

RESTAURANT RECOMMENDATIONS

Limones
Upscale Mexican and delicious — no burritos or enchiladas on this menu!
13 Eagle Street
828-252-2327

Doc Chey-Casual
A healthy, fresh noodle shop incorporating both Thai and Chinese influences.
No reservations, but their service is quick.

Bouchon
A fun, casual French bistro run by a Frenchman from Lyon. All you can eat mussel nights on Mon, Tues and Wed. The French fries with a mayonnaise-based sauce are to die for! No reservations.

12 Bones
A BBQ joint known for their ribs with blueberry sauce. Obama ate here while staying at the Grove Park where he prepared for one of his debates. It's on River Road: not walking distance. You'll need a car or cab.

Mela
An Indian restaurant with many variations.
20 N. Lexington
828-225-8880

Table
Memorable meals. Ingredients are mostly local and are deliciously prepared.
48 College Street
828-254-8980

Salsa
Caribbean/Mexican mix. Different, delicious and usually jammed with folks.
6 Patton Avenue
828-252-9805

French Broad Chocolate Lounge
Handcrafted chocolates, truffles, etc. Imaginative ingredients are in the truffles, such as coffees, teas and hot chocolate.

Early Girl Eatery
Southern dishes using local ingredients.
8 Wall Street
828-259-9292

Tupelo Honey
Southern dishes with an upscale twist. Great collard greens. Upscale Southern Food. Great Shrimp and Grits. Charming atmosphere overlooking one of the main public squares downtown.
12 College Street
828-255-4863

Laughing Seed
Only Vegetarian and good.
8 Wall Street
828-252-2639

Zambra
A tapas bar.
85 Walnut Street
828-232-1060

Nova Inventive
An upscale, hard-to-pin-down restaurant downtown. Also, relatively close to the Renaissance. They make their own mixed drinks from scratch, which are very good. The food comes in smaller portions, not quite tapas, but small enough to encourage trying several different dishes.

LOCAL BREWERIES

Some local brands, with various brews, are Highland, Pisgah, Green Man, Asheville Pizza and Brewing.

Jack of the Wood
95 Patton Avenue
828-252-5445

Pisgah Brewing Co. (Black Mountain)
Brew & View: Movies for $3.00, good food and watch a movie while you eat.
675 Merrimon Avenue (north of downtown)
828-669-2491

CRAFTS

Grovewood Gallery
In a separate building but on the grounds of the Grove Park Inn. Be sure to browse upstairs where there is large handcrafted furniture. Next door is a fun antique car museum.

Blue Spiral One
Downtown Gallery on S. Biltmore Avenue. Has fun exhibits, usually southern artists.

New Morning Gallery
Located in Biltmore Village.

FUN THINGS TO DO OUTSIDE OF DOWNTOWN

Biltmore Village
Just south of town at the entrance to the Bilmore House. This residential village was built by George Vanderbilt to house the laborers who built his home. He also built All Souls Church for the employees, which is now the Episcopal Cathedral for Western North Carolina. The village now houses many shops. ***Chelsea's*** and ***Corner Kitchen*** are two good restaurants for lunch.

NC Arboretum
A terrific 434 acre site devoted to native flora. Hiking trails and exhibits. I-240 to I-26 South. Exit at the NC Arboretum/ Biltmore Square Mall. Also accessible right off the Blue Ridge Parkway near Asheville with trails, flower and horticultural exhibits to name a few.
www.ncarboretum.org/

Blue Ridge Parkway
Just beyond the entrance to the NC Arboretum is the entrance on to the Parkway. Just 10 or so miles up the way is the ***Pisgah Inn***, a delightful restaurant on top of the Parkway. Not far but the temperature is certain to be 10 -15 degrees less than in downtown Asheville. Lots of great hiking all along the parkway (see entry below for a beautiful drive).

Pisgah Slide
Left on Hwy 276, south from Pisgah Inn, towards Brevard are Looking Glass Falls, Pisgah Slides (large rock which you can slide down (where OLD bathing suit with OLD shorts) and Looking Glass Rock (6 mile round trip hike).

Black Mountain, NC
A cute small town only 20 minutes east of Asheville just off I-40. Great local crafts. Be sure to eat lunch at ***The Verandah***, one of the best lunch spots in all of Western North Carolina. Always busy.

Chimney Rock Park
An hour's drive past Black Mountain on Hwy 9 (or south through Fairview on Hwy 74). The state has just bought this park. Nice hikes and great views.

Southern Highlands Craft Guild
Allanstand Craft the Blue Ridge Parkway near Asheville. Handmade crafts to support the crafts heritage of the Southern Blue Ridge.
www.southernhighlandguild.org/

Craggy Gardens
15 miles (30 min. or so) north of town on the Parkway are some great hikes and picnic areas in an area called Craggy Gardens. The hikes weave through a small bald filled with lots of rhododendron and wildflowers (hence the "gardens") and the views are incredible. The trails are not strenuous and you can hike to the top and back in around 45 min. The parkway around Craggy has been closed this spring for repairs, making access tricky, but it will probably be reopening at the end of May. Mount Mitchell, the highest point east of the Mississippi, is just about 15 minutes north. You can essentially drive to the top.

Mount Pisgah
This is another great hike, about 30-40 minutes south of the parkway. Mt. Pisgah is one of the major landmarks on the Asheville "skyline" — the big mountain in the distance with a big tower on the top. The hike is definitely more strenuous and about 1.5 to 2 hours, down and back, depending on how long you linger at the top. The views are lovely and one of the best parts is that you can have a hearty meal afterwards at the ***Pisgah Inn***, right near the start of the hike on the parkway. The ***Inn*** and its dining room have some incredible views of ***Pisgah National Forest*** below.

Bent Creek Experimental Forest
A third non-parkway option is to go to the ***Bent Creek Experimental Forest***. These two parks on the south end of town share several mountains and the valley which they enclose, backing up on ***Pisgah National Forest***. The arboretum has some lovely gardens and walking trails through the woods and ***Bent Creek*** has some truly great mountain biking. There is a mountain bike store near the entrance where bikes can possibly be rented, but bikes can be rented at most bike stores around Asheville.

NIGHT LIFE/MUSIC

Orange Peel
An Asheville treasure. On the edge of downtown, this music hall manages to pull some big names, while retaining an intimate feel. Bob Dylan and the Indigo girls have come, as have a number of bluegrass legends.

The Grey Eagle
Another Asheville treasure. Down in the same River Arts District, ***The Grey Eagle*** is a relatively small warehouse building that hosts a mix of great indie bands and smaller local groups. They also do contra dancing on certain nights of the week. There is a bar in the back and the space is incredibly intimate.

Barley's
On the main drag in downtown, Biltmore Ave., between Pack Place and ***The Orange peel***. They have food, but the highlight is the wide range of local beers they have on tap.

Hannah Flannagan's
The requisite Irish Pub across the street from ***Barley's*** on Biltmore Ave.

ABSTRACTS

SESSION 1: NUMERICAL MODELING OF DISCONTINUOUS MEDIA

ARMA 09-005

Three-Dimensional Discontinuous Deformation Analysis (3-D DDA) with Nth–Order Polynomial Displacement Functions

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Pooyesh Rah Mandegar Consulting Engineers, Tehran, Iran

Yeung, M.R.
Department of Civil Engineering, College of Engineering, California State Polytechnic University, Pomona, CA, USA

ABSTRACT: In the original 3-D DDA formulation, first-order displacement was assumed for block deformation, which precludes the application of it to problems with significant stress variations within blocks. This may yield unreasonable results when the block deformation is large and geometry of the block is irregular. Up to now, 3-D DDA with third-order displacement functions is developed. However, there are applications that may require using polynomials greater than the third-order to achieve better accuracy. This study presents the results of an effort to develop a more general approach in which the 3-D DDA is implemented with higher-order polynomial displacement functions. In this research, formulations of stiffness and force matrices in nth-order are presented and the codes have been programmed. An illustrative example is used to validate the new formulations and codes for different orders of displacement functions. By contrast, the results calculated for the same model by use of the thirdorder 3-D DDA are far from the theoretical solution.

ARMA 09-047

Modeling Variation of Stress and Permeability in Naturally Fractured Reservoirs Using Displacement Discontinuity Method

Tao, Q., Ehlig-Economides, C.A. and Ghassemi, A.
Department of Petroleum Engineering, Texas A&M University, College Station, TX, USA

ABSTRACT: Fractures are the main channels of production in naturally fractured reservoirs, therefore the fracture permeability is a key parameter to production optimization and reservoir management. The perturbation of effective stress acting on a fracture can change the fracture aperture, thereby changing the fracture permeability. Pressure depletion in a naturally fractured reservoir can result in effective stress change that, in turn, can change fracture permeability. The displacement discontinuity method is a boundary element method with the ability to handle the rock discontinuities and fractures. The coupled poroelastic displacement discontinuity method also involves into the interaction of fluid flow and the discontinuity. A nonlinear mechanical model is applied to represent the fracture deformation including normal and shear deformation. In this work we apply displacement discontinuity method combining with the fracture deformation model to model the variation of stress and fracture aperture and resulting permeability variation during production in naturally fractured reservoirs.

ARMA 09-065

Coupled Thermal/Fracturing Process of Rocks

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H.M. Kim and E.S. Park
Korea Institute of Geoscience & Mineral Resources, Daejeon, South Korea

T.K. Kim, J.M. Lee and H.S. Lee
SK E&C, Seoul, South Korea

R. Junker
Leibniz Institute for Applied Geosciences (LIAG), Hannover, Germany

M. Rinne
FRACOM Ltd., Kyrkslätt, Finland

T. Backers and T. Meier
GeoFrames GmbH, Potsdam, Germany

Ove Stephansson
Helmholtz Center Potsdam, GFZ German Research Centre for GeosciencesGeoForschungsZentrum, Potsdam, Germany

ABSTRACT: The paper describes a recent numerical code development and laboratory investigations on coupled thermal-mechanical processes of rock fracture propagation. The numerical development is based on a fracture mechanics code FRACOD that has previously been developed by some of the authors of this paper. The code simulates complex fracture propagation in rocks governed by both tensile and shear mechanisms. For the latest development an indirect boundary element method, namely the fictitious heat source method, is implemented in FRACOD to simulate the temperature change and thermal stresses in rocks. This method is particularly suitable for the thermal-mechanical coupling in FRACOD where the displacement discontinuity method is used for mechanical simulation. The coupled code has also been extended to simulate multiple region problems with different thermal and mechanical properties. This paper also describes the recent laboratory investigations on rock strength and fracture toughness within a temperature range from -60°C to 250°C. An application case is presented where a pilot LNG underground cavern operated by SKEC at Daejeon, South Korea is studied using the coupled code. The code simulates the cases where excavation, concrete lining and thermal insulation layer are all present. A good agreement has been obtained between the FRACOD simulation and the actual field measurement data in the pilot LNG cavern.

ARMA 09-121

Thermo-poroelastic Finite Element Analysis of Rock Deformation and Damage

Lee, S.H. and Ghassemi, A.
Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, Texas, USA

ABSTRACT: Rock failure and permeability change is of interest in a number of reservoir geomechanics problems such as induced seismicity and near wellbore mechanics. Temperature and pore pressure variations play an important role in this context and their contributions need be considered. In this work, we develop a fully-coupled thermo-poro-mechanical finite element model with stress dependent permeability and consider the rock shear and tensile failure based on damage mechanics and consideration of heterogeneous rock strength distribution. The model is applied to the problem of injection into a reservoir with reference to reservoir stimulation in geothermal and petroleum reservoirs.

ARMA 09-029

Experimental Study and PFC Modelling of Failure Process of Brittle Rock Under Uniaxial Compression

Ming Xia and Keping Zhou
Central South University, Changsha, Hunan, P.R. China

Baoping Zhao
Three Gorges University, Yichang, Hubei, P.R. China

ABSTRACT: Using the MTS815 Full-Digitally Servo-Controlled Rock Mechanics Testing Machine, three different types of brittle rocks retrieved at the 1870 Level of the Kafang Mine are tested in the laboratory experiments under uniaxial compression. Four different failure patterns are observed during this test. Most common failure patterns are axial splitting, V-shaped failure, Xshaped and shear failure as well. The 2-dimensional particle flow code (PFC2D) was used in the numerical simulations because of its capability in modelling the behavior of brittle rock material including fracture propagation. Contact-force distribution, crack distribution, stress–strain response and damage patterns formed during uniaxial compression tests are observed. The parameters used in the numerical simulations are calibrated when rock parameters such as uniaxial compressive strength, elastic modulus and Poisson's ratio, are in agreement with the experimental results. Splitting and faulting failure modes frequently

observed during laboratory experiments of rocks under uniaxial compression are also reproduced in the simulations. Damage formation during the compression simulations indicated that the PFC2D modeling could simulate the events happening during the laboratory compression tests of rock samples by reproducing similar fracture generation and deformation.

SESSION 2 : UNDERGROUND SUPPORT DESIGN

ARMA 09-182

Stress Corrosion of Rockbolts in Australian Coal Mines

Craig, P.
School of Mining Engineering, UNSW and Jennmar Australia, Sydney, Australia

Saydam, S. and Hagan, P.
School of Mining Engineering, UNSW, Sydney, Australia

ABSTRACT: Stress corrosion cracking (SCC) has been reported to be a significant cause of premature failure of rockbolts in Australian coal mines. At some mine sites, failure of rockbolts due to SCC has occurred well within the twelve to eighteen month design life of longwall gateroads. Failure is often associated with installations in coal and carbonaceous shales containing clay bands. The use of very high tensile grade steel is commonly used in many of these mines and it is thought that the low impact toughness of this steel may be a significant contributor to SCC failure. While laboratory corrosion studies have been undertaken to assess the metallurgical influence on SCC, the results do not correlate with field observations. A possible contributor to the enhanced incidence of premature failure in recent years may be due to the increase in extraction width from 250 m to 400m in many Australian longwall mines that can lead to an increase in the loading on the rockbolt. This paper examines the current state of knowledge concerning rockbolt failure in Australian coal mines.

ARMA 09-004

Investigation of Thin Spray-On Liners Using Numerical Modeling

Richardson, J.
School of Mining Engineering, The University of New South Wales, Sydney, NSW, Australia

Mitra, R. and Saydam, S.
School of Mining Engineering, The University of New South Wales, Sydney, NSW, Australia

ABSTRACT: Rock support is the basis of any underground mine and many open cut operations. Ground support methods have evolved over the years with the current trend to use bolts, mesh and shotcrete. In the last decade there has been a significant growth in the number of commercially available thin spray-on liner (TSL) products. It is a common opinion that TSL products, as part of a complete ground control system, may present significant benefits for operations. Numerical modeling techniques are regularly used for research and design purposes. It can be effectively applied in the field of geomechanics in order to assist in the interpretation and prediction of results. The bending and the double-sided shear tests are the two laboratory tests that are designed to evaluate the properties of different TSLs. This paper evaluates the use of numerical modeling to simulate the material properties and support action of TSLs. The purpose of this study is to further develop modeling techniques for the simulation of TSL materials. This paper discusses the methodology and results of simulating these laboratory tests using the FLAC finite difference modeling software.

ARMA 09-093

Geologic Evaluation, Roof Stability Analyses, and Ground Support Design for Underground Mine Slope Entries

Kevin J. Ma and John Stankus
Keystone Mining Services, LLC of Jennmar Corporation, Inc., Pittsburgh, PA, USA

Mitra, R. and Saydam, S.
School of Mining Engineering, The University of New South Wales, Sydney, NSW, Australia

ABSTRACT: Proper evaluation of geological conditions and stress environment are critical to ground control in underground openings. For a slope entry, the problem becomes more complicated due to the fact that the entry normally digresses through different types of strata before reaching the coal seam. Furthermore, as the depth increases, the stress level changes. Therefore, it is important to determine the stress distribution and evaluate stability of the opening along different slope sections when designing roof bolting plan and long term ground support. Over the past two years, Keystone Mining Services, LLC of Jennmar Corporation Inc. has developed a new methodology, designated as the Stress, Geologic, Support design system (SGSsm), for underground mine openings. This methodology has been successfully applied in various coal mines across USA. Through an application at an underground slope mine, this paper briefs main concepts of the methodology and details the following: (1) Geological evaluation and stress analysis along the slope utilizing numerical modeling and the identification of strong, fair, and weak sections along a slope; (2) Design of primary and supplemental bolting plans for each section along the slope. (3) Design of long term standing support in the form of steel sets based on the current industry standards by the American Institute of Steel Construction (AISC); and (4) Validation and performance evaluation of the designed steel set structure under extreme loading conditions using numerical modeling techniques.

ARMA 09-032

The Application of a Structural Thin Support Liner (TSL) on Mines

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Southern Illinois University Carbondale, Carbondale, Illinois, USA

Borejszo, G.
South African Mining & Engineering Supplies, Krugersdorp, Gauteng, South Africa

Campoli, A.
Jennmar Corp., Pittsburgh, Pennsylvania, USA

ABSTRACT: Thin support liners (TSLs) have been used since the 1980s mainly to limit the weathering of rock. Numerous attempts have been made to create viable structural TSLs that can effectively replace 30 to 60mm of un-reinforced shotcrete (sprayed concrete) with only limited success. The structural use of TSLs is now gaining acceptance as the historical performance issues associated with them are resolved. These performance issues have been mainly associated with the long term stability of the polymer particularly under high humidity conditions and application issues related to equipment and pot life. Tunnel Guard is the most widely applied TSL internationally with sustained sales of over 1,000 tons/month in Southern Africa alone. This is enough material to cover almost 100,000 m² of exposed excavations per month. The applications in Southern Africa are mainly on deeper level tabular gold mines but the product is also used in platinum, diamond and copper mines for weathering protection and for structural support. This paper investigates the performance and cost effectiveness of the product mainly compared with shotcrete.

ARMA 09-203

Working Safely Under Inverse Raise Boreholes at Brunswick Mine: The Story of the "Trampoline"

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ABSTRACT: Inverse raise boreholes, 0.762m (30") diameter and up to 22m long are used at Xstrata Zinc Canada's Brunswick Mine as inverse slot raises to make room for production upper blast holes. Working under these big and long open boreholes (for production drilling and blast loading) cannot be allowed unless a tough back mounted rock fall protective device is installed. This paper describes a compact device that was developed at Brunswick Mine and dubbed the "trampoline". It is constructed of a heavy gage chain link mesh reinforced by air craft steel cables interlaced. Two steel plates with a "comb" like shape hold the net and help to affix it to the back with conventional ground support hardware.

SESSION 3: BOREHOLE GEOMECHANICS AND DRILLING I

ARMA 09-026

A Strain-Softening Model for Drilling-Induced Damage on Boreholes in Williston Basin

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ABSTRACT: Plastic yielding is evidently present when the borehole instability occurs, thus the elasto-plasticity constitutive model is an appropriate choice for mechanically representing the geologic materials of the borehole wall. In this paper, taking advantage of the field data of the geological formations in the Williston Basin, North Dakota, together with the experimental data from laboratory tests, we investigate the borehole instability problems using a strain-softening elasto-plasticity model. The strainsoftening model implemented in a numerical program is applied to simulate the drilling process. The simulations show that the chosen model is capable of capturing the localization characteristics at the post-peak stage, and the tensile and shear damages inside the borehole wall. Based on numerical simulation results, the distribution of displacements, stresses, damage zones and the strain localization and their influences on the borehole stability are systematically analyzed. In addition, the effects on the borehole stability of other factors such as stress path, drilling fluid pressure and well orientation are also explored.

ARMA 09-097

Rock Mechanical Modelling for an Underbalanced Drilling Rate of Penetration Prediction

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ABSTRACT: Accurate knowledge of rock strength is essential for drilling optimization and rate of penetration (ROP) prediction. Conventional drilling simulators provide a tool to generate rock strength for the drilling engineer to further model and study the effect of different drilling parameters which can optimize the overall drilling process performance. Experience shows that the best correlation is generated from actual drilling data which consider the effect of drilling and bit design parameters on rock strength. The work presented herein focus on generating rock strength based on the geological and drilling data from offset wells to generate the rock strength for the underbalanced drilling (UBD) condition. The scope of the paper is divided into the following phases:

1 Theoretical development of the rock strength correlation needed in the ROP modeling where both the overbalanced and underbalanced drilling condition is considered.

2 Prediction of bottom hole pressure for UBD operations with aerated or foam drilling

3 Correlation from the confined compressive strength (CCS) under either underbalanced or overbalanced drilling conditions to uniaxial drilling strength.

4 Verification using actual drilling data to predict ROP and compare it to field data from UBD operations using the ROP models

The application of this work links a UBD bottom hole prediction program and drilling rock strength in a ROP drill bit model, which results in a UBD drilling simulator that is a great preplanning tool for drilling engineers.

ARMA 09-138

Casing Integrity in Hydrate Bearing Sediments

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ABSTRACT: An axisymmetric numerical model that investigates casing and formation integrity in gas hydrate bearing sediments has been created using FLAC3D. The model simulates a vertical wellbore drilled in cemented sandy sediments. The middle layer of sediments can be cemented with an appreciable amount of gas hydrate entrapped in the pore space. The other two layers are cemented with a stable non hydrate material. It is found that the maximum von Mises stresses occur at the top of the casing. Heating the casing causes the von Mises stresses of the casing to increase along the casing profile but not at the top of the casing. The design of a string of casing is based on the minimum safety factor which corresponds to the maximum von Mises stress value calculated at the top of the casing. There has been no appreciable difference noted in the von Mises stress response of the casing whether or not the sediments contained hydrates. Additional compressive hoop stresses are generated in the casing as heating continues and the pore pressure increases in the formation due to fluid expansion and hydrate dissociation. These stresses are larger when the casing is placed through a hydrate bearing layer. Nevertheless the absolute maximum thrust in the casing drops upon heating the casing and the wellbore. This maximum thrust occurs at the top of the casing for all the cases studied and is detected close to the base of the hydrates layer in case of its presence after 4 days of heating. No risk of hydrostatic buckling is found.

ARMA 09-027

Measurement of Conical Bit Rotation

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ABSTRACT: This paper will discuss the process of rock cutting with conical bits with emphasis on bit rotation. This includes discussion of importance of bit rotation and its impact on bit life. The paper will review the rock cutting process and related parameters, objectives of the current study, and the status of full scale cutting tests being performed in Kennametal Inc, rock cutting laboratory in Latrobe PA. The testing will include different bit types cutting parameters, and skew angles to identify most influential factors on bit-rock interaction pertinent to bit rotation. A series of full scale linear cutting test are underway and the preliminary results will be discussed in this paper. These tests will be followed by rotary cutting test where the instrumented bits are mounted on a drum for full scale testing and monitoring of bit rotation in rotary cutting tests.

ARMA 09-067

Strengthening a Wellbore with Multiple Fractures: Further Investigation of Factors for Strengthening a Wellbore

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ABSTRACT: Lost circulation is a common drilling event; however, it may result in severe consequences. Wellbore strengthening as a new concept has led to improved products and performance for fighting lost circulation in the field. Although many different technologies can be applied to effectively control the well and cure the mud losses, preventive wellbore strengthening technologies are always preferred for apparent reasons.

A wellbore strengthening technology, sometimes called as stress cage treatment [1,2], has been recognized as an effective solution to lost circulation. To better understand the underlying technology and improve performance in the field, studies have been conducted based on modeling borehole behaviors under various conditions. Some results [3-7] have been published based on a model with one fracture penetrating the wellbore. However, in reality, it is possible that more than one fracture could exist. Knowing how a wellbore will behave under multiple-fracture conditions is recommended for engineers when designing a treatment or formulation to cope with the challenge from various lost circulation conditions.

Following previous discussions, further study with numerical analysis on a multiple-fracture model has achieved a critical understanding that, among a multiple-fracture system, very likely there is a primary fracture that controls the wellbore pressure containment. A wellbore strengthening job can rely on the understanding of the behavior of this governing fracture.

SESSION 4: NATURAL DISCONTINUITIES–CHARACTERIZATION AND MODELING

ARMA 09-068

Seismic Wave Propagation in Fractured Carbonate Rock

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ABSTRACT: Laboratory experiments were performed on cubic samples of aluminum and Austin Chalk to investigate the effect of fabric-induced anisotropy on the interpretation of fracture specific stiffness. Seismic data were analyzed using the displacement discontinuity theory for wave propagation across a single fracture. For the aluminum standard, the theory successfully simulated the effect of a synthetic fracture seismic wave transmission and both normal and shear fracture specific stiffness were estimated. However, fractures specific stiffness could not be interpreted for the Austin Chalk samples because of the layering in the sample. Wavelet analysis of the Austin Chalk data showed that multiple reflections between layers caused constructive-destructive interference which attenuated the high frequency components of the signals from the intact sample. The presence of the fracture interrupted the interference and enabled high frequency components to be transmitted through the fractured sample.

ARMA 09-059

Application of Synthetic Rock Mass Modeling to Estimate the Strength of Jointed Sandstone

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ABSTRACT: This paper is a case study on the estimation of rock mass strength for jointed sandstone using Synthetic Rock Mass (SRM) modeling. The case study broadly follows the SRM approach described by Cundall et al. (2008). First the strength and elastic response of intact rock are quantified in laboratory experiments including Uniaxial Compressive Strength, Brazilian, and Tri-axial tests at confining pressures from 1, 5 & 10 MPa. Second, a Bonded Particle Model loaded in uniaxial compression is calibrated to the laboratory measured strength and deformation parameters. Third a three dimensional synthetic rock mass is formed through the introduction of joint sets in random locations and orientations, using the Smooth Joint Model (SJM). The SRM is then subjected to a range of stress states and stress paths to estimate the yield criteria and rock mass modulus for a range of fracture frequencies.

ARMA 09-145

A Numerical Investigation of Scale Effects on the Behavior of Discontinuous Rock

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ABSTRACT: In numerical simulations of mining induced problems, it is not possible to represent discontinuities at all length scales. However, all length scales are coupled, so the homogenisation process and the selection of what discontinuities must be represented explicitly should be rigorous. To investigate some homogenisation concepts for mine problems, the load-deformation response of some discontinuous rock masses at an example mine have been simulated using Explicit, Finite Element models. The intent of the analysis was to investigate the effects of specimen size and confining stress on strength, dilation and comminution. The analysis is used as a basis for a discussion of some preliminary ideas and concepts for deciding what length scale of structures need to be included in numerical models of mining deformation.

ARMA 09-054

Anisotropy of the Strength, Deformability, and Dilatancy of Rock Fractures

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ABSTRACT: Among the constitutive models for rock fractures developed over the years, Barton's empirical model has been widely used because it is easy to apply and includes several important factors associated with fracture characteristics. Anisotropic behavior of rock joints were investigated experimentally by different researchers. They proposed models that can deal with the strength, deformability, or dilatancy of rock fractures. These models include several parameters and they are much more complicated than Barton's model. Experimental data found in the literature are used in this paper to formulate a method to simulate anisotropic behavior of rock fractures in accordance with Barton's model. The shear strength, shear stiffness, and dilation displacement of rock fractures subjected to shearing in all directions can be predicted using the proposed model applied on Barton's failure criterion parameters.

ARMA 09-154

Three-dimensional Poroelastic Displacement Discontinuity Simulation of Natural Fractures

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ABSTRACT: A three-dimensional fully-coupled poroelastic displacement discontinuity method is developed and used to analyze the temporal variation of opening and slip of a natural fracture in a reservoir in response to the sudden application of fluid pressure on the fracture surfaces. Numerical results show that a hydraulic fracture opens in an increasing manner with time as the rock moves towards a drained state under the applied stress. The applied pore pressure induces a time-dependent closure caused by the rock dilation. On the other hand, poroelastic analysis of a natural fracture subjected to shear shows that the fracture slip decreases with the time in response to a pore pressure-induced increase in the normal stresses on the joint

ARMA 09-144

A Computational Study: The Scaling Relationship Between Fluid Flow And Displacement In Single Fractures

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ABSTRACT: Experimental studies have shown that fracture specific stiffness and fluid flow through a fracture are implicitly related through the geometry of the fracture. We investigated numerically the fundamental geometric lengths scales that affect fracture deformation and fluid flow with the goal of developing a scaling relationship between this two fracture properties. We examined the displacement-stress and flow-stress relationships as a function of scale. Though deformation-stress and fluid flow-stress relationships differed for each simulated fracture or subset of a fracture, we were able to collapse the statistical fluctuations in these relationships by using zeroth order approach.

SESSION 5: CARBON SEQUESTRATION - FLOW AND MECHANICAL PROCESSES

ARMA 09-017

Coupled Hydromechanical and Reactive Transport Processes with Application to Carbon Sequestration

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ABSTRACT: Large-scale carbon capture and storage (CCS) projects are the central infrastructural element needed to substantially reduce greenhouse gas emissions in a decarbonized fossil fuel energy system. Predicting the ultimate fate of the injected CO_2 involves understanding the interrelationship between multiple processes. These processes change the pore space within the reservoir, potentially modifying the permeability tensor within the reservoir. Furthermore, the flow in many target reservoirs is fracture dominated and fractures by nature can exaggerate the interrelationship between different processes. We present results of an ongoing study of the different processes at work within a fractured reservoir target for CO_2 storage.

ARMA 09-030

Hydraulic Fracturing Mechanisms in Carbon Sequestration Applications

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ABSTRACT: Geologic carbon sequestration is becoming an increasingly viable method for reducing the rate of greenhouse gas emissions through the injection of CO_2 into geologic reservoirs. To be effective, this technology must be implemented on a large scale; however, several uncertainties remain about the effect of such large rates and volumes on individual reservoirs and whether this may present a failure risk. Hazards such as fault activation through increased pore pressure or creation of new fractures through the injection process remain significant risks for site failure. As part of a larger effort to understand the interrelationships between different failure mechanisms, we will focus here on the role of hydraulic fracturing in reservoir geomechanics. This study will detail efforts using a finite-discrete element code (LDEC) coupled with a 2-D finite volume solver for fluid flow through fractured rock. An overview of the approach will be provided as well as current results of a continuing study into the effects of hydraulic fracturing and fluid flow for a fractured CO_2 sequestration site. We will also discuss implications for broader successful implementation of geologic CO_2 sequestration.

ARMA 09-099

Investigation of CO_2 Injection Induced Coal-Gas Interactions

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ABSTRACT: Understanding the role of the co- and counter-diffusive properties of CO_2 and CH_4 in coal has important implications for enhanced coalbed methane recovery (ECBM) and CO_2 sequestration in coals and for related issues of gas outbursts during mining. This study addresses how coal-gas interactions affect CO_2 injectivity, in particular the roles of coal deformation, gas flow, CH_4-CO_2 counter-diffusion and gas absorption/desorption on the evolution of transport and mechanical properties of fractured coals, and therefore on ECBM recovery. A fully coupled coal deformation, gas flow, CH_4-CO_2 counter-diffusion and gas absorption/desorption finite element (FE) model was developed to investigate the combined net effects on evolutions of CO_2 injection related parameters. The FE model was successfully applied to match the experimental data; and a field scale model was constructed to quantify CO_2 injection rate and other transport parameters for ECBM under in-situ conditions. Model results indicated that (1) Coal rank has a converse influence on the CO_2 injection performance, lower coal rank reservoir could be more suitable to carry out CO_2-ECBM technology; (2) Initial permeability has positive impact on the performance of CO_2 replacing methane. This finding also has an important indication for the implementation of this technology in shale and other low permeability media; (3) CO_2 injection is very sensitive to changes in the injection gas Langmuir strain constants, so trying to reduce the resultant strain constant, such as using mixed gases like N_2 and CO_2 or flue gas, is an efficient solution to improve the methane recovery efficiency.

ARMA 09-164

Dual Poroelastic Response of Coal Seam to CO_2 Injection

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ABSTRACT: Although the influence of gas sorption-induced coal deformation on porosity and permeability has been widely studied, these studies are all under the invariant total stress condition. According to the principle of effective stress, the induced coal deformation is determined by the change in effective stress, which can be replaced by the change in pore pressure, under the assumption of null change in total stress. This is why terms representing effective stress or total stress are absent in all of these existing permeability models. In our previous work (Zhang et al, 2008), this assumption was relaxed and a new porosity and permeability model was derived. The FE model was also applied to quantify the net change in permeability, the gas flow, and the resultant deformation in a coal seam. In this work, the general porosity and permeability model was modified to represent both the primary medium (coal matrix) and the secondary medium (fractures), and implemented into a fully coupled coal deformation, CO_2 flow and transport in the matrix system, and CO_2 flow and transport in the fracture system model. The novel dual-poroelastic model was applied to quantify the mechanical responses of coal seam to the CO_2 injection under in situ stress conditions. The simulation results illustrate how the CO_2 injectivity is controlled both by the competition between the effective stress and the gas transport induced volume change within the matrix system and by the dynamic interaction between the matrix system and the fracture system.

ARMA 09-011

Laboratory Testing on Geomechanical Properties of Carbonate Rocks for CO_2 Sequestration

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ABSTRACT: Williston Basin, North Dakota, USA is predominated by carbonate successions from Cambrian through Cretaceous, followed by episodic glaciations through Quaternary. Geomechanical characterization of this rock succession is a critical element to understand the subsurface processes when conducting anthropogenic CO_2 sequestration. CO_2 sequestration can be divided into two stages. The first is to inject CO_2 to the target formation; and the second is to keep the injected CO_2 in the formation for a designed period of time, e.g. 1000 year. As rocks behave differently under deep reservoir conditions from that under atmospheric conditions, detailed studies of thermo-hydro-mechanical effects are needed. In this paper, effects of CO_2 sequestration on host rock are investigated through combined water-alternative- CO_2 injection and tri-axial geomechanical tests. Testing results indicate that rock strength can be decreased significantly after the first stage. In the second stage which is under static, no-flow conditions, there is no obvious difference in strengths between CO_2- and water-saturated rocks. It seems that CO_2 saturated rocks even tend to be more competent. This may reveal the different micro-cracking mechanisms caused by different molecular level properties such as wettability, etc. Linear Mohr-Coulomb criterion applied to drained testing results very well, but show discrepancy to those of un-drained testing.

SESSION 6: LIDAR AND REMOTE SENSING FOR ROCK MASS CHARACTERIZATION I

ARMA 09-098

The Use of Terrestrial Lidar in Determining Directional Joint Dilation Angle Values

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ABSTRACT: It is well documented in the field of rock mechanics engineering that joint roughness plays an integral role in the shear strength of discontinuities. The effective friction angle of a discontinuity includes both the saw-cut friction angle, ö, and the inherent natural roughness encountered on fracture faces. This second component is the joint dilation angle, and is the focus of this study. Emphasis is not on a preferred method of characterizing roughness, but rather a new technology as a tool to assist in analyzing joint roughness. Using ground-based laser scanning and point cloud processing software, joint dilation angles can be found by finding the angular difference between poles to a triangulated mesh and the mean pole. Simple vector operations can then project all poles onto a common surface (the fracture surface) and described as rakes on the plane. These two components make up the directional dilation angle, which seems to be a valid took based upon a case study performed at a site near the San Pedro Vista near Tucson. This directional dilation angle value may influence the directional shear strength, for example in a direction parallel to a dip direction of a joint. Future research will also include analyzing the relationship between this directional dilation angle and the overall structure of the rock mass in which it is found.

ARMA 09-123

Analyzing Lidar Data for Rock Mass Characterization Using a Fast and Simple Mesh-Less Technique

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ABSTRACT: This paper presents a new method for analyzing point cloud data of rock surfaces obtained using a ground based Lidar system. The method allows the user to specify a reference plane and a grid of cylinders used to sample the point cloud. Output from the program includes orientation and elevation plots on a rectangular grid, at user-selected resolution. Rock mass characterization is a fundamental part of every rock engineering project. This powerful data exploration tool is designed for maximum flexibility and efficiency. The technique allows the user to examine orientations, orientation distributions, mean elevations and variability on any selected scale, either in terms of absolute orientation or with reference to a selected reference plane. Examples of the application of this tool to rock surfaces from slopes and tunnels in Virginia will be given. The advantages of this new approach for fracture surface characterization will be demonstrated.

ARMA 09-181

Integrating GIS-Based Geologic Mapping, Lidar-based Lineament Analysis and Site Specific Rock Slope Data to Delineate a Zone of Existing and Potential Rock Slope Instability Located Along the Grandfather Mountain Window-Linville Falls Shear Zone Contact, Southern Appalachian Mountains, Watauga County, North Carolina

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ABSTRACT: Landslide hazard maps of Watauga County identify >2200 landslides, model debris flow susceptibility, and evaluate a 14km x 0.5km zone of existing and potential rock slope instability (ZEPRSI) near the Town of Boone. The ZEPRSI encompasses west-northwest trending (WNWT) topographic ridges where 14 active/past-active rock/weathered rock slides occur mainly in rocks of the Grandfather Mountain Window (GMW). The north side of this ridgeline is the GMW / Linville Falls Fault (LFF) contact. Sheared rocks of the Linville Falls Shear Zone (LFSZ) occur along the ridge and locally in the valley north of the contact. The valley is underlain principally by layered granitic gneiss comprising the Linville Falls/Beech

Mountain/Stone Mountain Thrust Sheet. The integration of ArcGIS™ - format digital geologic and lineament mapping on a 6m Lidar (Light Detecting and Ranging) digital elevation model (DEM) base, and kinematic analyses of site specific rock slope data (e.g., presence and degree of ductile and brittle deformation fabrics, rock type, rock weathering state) indicate: WNWT lineaments are expressions of a regionally extensive zone of fractures and faults; and ZEPRSI rock slope failures concentrate along excavated, north-facing LFF/LFSZ slopes where brittle fabrics overprint older metamorphic foliations, and other fractures create side and back release surfaces.

ARMA 09-155

Statistical Characterization of Rock Structure using Lidar

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ABSTRACT: When designing with rock masses of relatively high intact strength, characterization of the geologic structure properties is a critical component to proper analysis. Data describing distributions of discontinuity orientation, length, spacing and strength for pertinent sets within the rock mass provide the basis of probabilistic models necessary for analysis. Probabilistic methods require a reasonably large sample size in order to provide reasonable estimates of inherent structural variability. The use of laser scanning, or Lidar, technologies is commonly utilized as a high resolution survey technique but is less frequently used, in conjunction with registered high resolution digital imaging, as a tool for geotechnical data collection. This methodology can provide a cost effective and time efficient means of collecting such large data sets. A case study was carried out to evaluate the correlation between statistical characterization of discontinuity properties acquired manually in the field using oriented core and cell mapping techniques to those obtained remotely using Lidar. The benefits and limitations of these methods are evaluated and practical recommendations are made based on results of the case study.

ARMA 09-122

A Comparison of Photogrammetry and Laser Scanning for the Purpose of Automated Rock Mass Characterization

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ABSTRACT: The acquisition of 3D data using Lidar or photogrammetry represents an improvement over traditional field methods in terms of data collection rate and direct digital documentation, and applications of 3D digital imaging in rock engineering are becoming quite prevalent. A direct comparison of the two technologies was conducted in this study in order to assess their relative merits in terms of field implementation, processing, data collection, and analysis. Total field time for both methods was nearly identical but photogrammetry required more post-processing. For the rock outcrop studied here, photogrammetry provided a much denser 3D point cloud, produced a finer surface model, and was able to identify nearly three times as many discontinuities within the rock mass compared to the laser scan derive point cloud.

SESSION 7: FRAGMENTATION, EXCAVATION AND CAVING

ARMA 09-153

Discrete Element Modeling of Impact Fragmentation in Rock Fall Analysis

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ABSTRACT: A DEM code has been used to simulate impact induced rock fragmentation in rock fall analysis with a simplified impact model inspired by the theory of dynamic foundation. It has been shown that the magnitude of impact velocity, the angle of the incidence, the ground condition all play very important roles in impact fragmentation. Energy transformation during impact is tracked to reveal the energy loss associated with fragmentation and geometric damping. The fragmentation size distribution can be well represented by a two-parameter Weibull distribution.

ARMA 09-160

Calibration of 3D Cutter-Rock Model with Single Cutter Tests

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ABSTRACT: Much of our nation's future supplies of oil and natural gas for our energy needs are expected to come from deep formations in High Pressure and High Temperature (HPHT) environments. Optimizing the drilling performance in these HPHT operations is crucial to successful, economic mineral extraction, and a better understanding of the cutter-rock interaction in these conditions is vital to optimize drilling performance. To investigate the cutter-rock interaction, a 3D numerical single cutter model was developed. In this paper, the 3D model results are calibrated and compared with single cutter laboratory tests from the literature.

The calibration of the 3D numerical model with the laboratory single cutter tests was primarily accomplished by matching the average vertical and horizontal loads on the cutter between the model and the laboratory tests. For the rock properties, the bulk modulus, shear modulus, cohesion and internal friction angle of the rock were determined by back analyzing uni-axial and tri-axial test results from the literature. Also, a strain-softening Mohr-Coulomb failure criterion was used for the rock. The separate effects of the model properties on the cutting forces were individually investigated in a small parametric study. In this study, the interface friction and stiffness properties, and the peak- and post-failure parameters of rock were individually changed, and the effect of these changes on cutter forces were analyzed. Finally, the parameters which best matched the 3D model's cutter forces to the single cutter test data were determined.

ARMA 09-070

Disturbed Gravity Flow in Block Caving

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ABSTRACT: In block caving, most existing knowledge of the mechanisms controlling gravity flow comes from idealized numerical and scaled physical modeling experiments on gravels and sands with narrow particle size and shape distributions. By contrast, actual block caves are known to have large discrete blocks, or interlocking groups of particles, which travel through the cave, resulting in hang-ups and other disturbances to the gravity flow stream or displacement field. Three fundamental types of disturbed flow are presented in this paper namely: static, kinematic and mixed mode flow. Static disturbance is the result of the formation of a stationary zone of particles, which blocks or disrupts the flow of smaller particles. Kinematic disturbance results from differential movements between the fine and large size fractions. Mixed mode disturbance is a combination of static and kinematic disturbance. The flow mechanisms for each disturbance mode are explored, and the implications to block caving considered.

ARMA 09-092

Extent of Damage Associated with the Passage of the Compressive Stress Wave Generated by Blasting

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ABSTRACT: Unwanted damage to the roof and walls of underground openings due to poor blasting practices presents a safety hazard to miners. The Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) is currently conducting a program aimed at studying ways of minimizing such perimeter damage to rock masses during blasting. When a cylindrical charge detonates in a borehole, the generated shock wave travels outward away from the hole. This wave has both compressive and tensile components and is thought to be largely responsible for the new crack generation. In the second stage of the blasting process, the gas pressure works to open and extend both the new and existing cracks. Because of the importance of the shock wave action, several different techniques are being used to quantify its effect. This paper presents the results obtained from a well-controlled, highly instrumented, single-hole blast conducted in a large concrete block together with supporting laboratory test data. Special laboratory tests, which involved the use of the Hustrulid Bar apparatus performed on long cores taken from the block, provide dynamic compressive strength values as well as the stress amplitude attenuation factors appropriate for the crushing, transition and seismic zones. A theoretical expression for the amplitude of the generated compressive wave as a function of distance from a cylindrical charge based on the introduction of attenuation factors was developed. This expression was then used to predict the compressive stress amplitude at different distances resulting from the detonation of a fully-coupled cylindrical charge of Dyno AP® in the concrete block. The blast-generated compressive stress wave was measured using strain gage instruments. The instruments consisted of five grout bars with one strain gage rosette at the end that were grouted directly into the block. The predictions, based upon the Hustrulid Bar tests and cautious blasting theory, were found to agree well with observed damage limits in the concrete block.

ARMA 09-110

Effect of Seam Dip on Face Orientation of Longwall Top Coal Caving

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ABSTRACT: This paper describes the results of numerical analysis on the effect of seam dip on face orientation of Longwall Top Coal Caving method for extraction of inclined thick coal seams. The study was aimed at investigating the differences in caving mechanism of the top coal and the above rockmass when extracting in inclined thick seams by the Longwall Top Coal Caving method in three different directions of inclined thick seams: along strike, up-dip, and down-dip. The analysis outcomes demonstrate that face retreats along strike has a better cavability as compared to the other directions.

SESSION 8: BOREHOLE GEOMECHANICS AND DRILLING II

ARMA 09-040

Drillability of a Rock in Terms of its Physico-Mechanical and Micro-Structural Properties

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ABSTRACT: Drillability of a rock is often expressed in terms of a large number of parameters; however, the industry hardly uses any. Quite often these are not well understood or communicated to the end users. As a compromise, the present work describes drillability in terms of eight simple physical, mechanical, and micro-structural properties, which are displayed visually and are available from either log data or from laboratory core testing. The relevant rock properties are density, porosity, compressional and shear wave velocities, unconfined compressive strength, Mohr friction angle, mineralogy, and grain sizes. These are compiled and normalized in a scale of 1 to 8; value of 1 represents very soft rock and a value of 8 represents hard rock, ideally.

The real rock is in between depending upon the rock type. The plot is called a "spider plot," which characterizes drillability fully in simple enough parameters for use in the industry, yet detailed enough to describe drillability issues to a great extent. Further, this gives an excellent tool to optimize the bit and drilling process for a given rock formation while depicting its physico-mechanical and micro-structural properties as a signature plot.

ARMA 09-170

Changing Shale Strengths with Invert Emulsion Drilling Fluids: Theory and Measurement

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ABSTRACT: Problems with wellbore stability while drilling in shale have plagued the drilling industry for a long time. For good reason, the bulk of trouble-related problems while drilling have been in shales, and great expenditures in time and money are made each year dealing with the problem. However, shale interaction with drilling fluids in the drilling process remains a complex and often misunderstood area of study. Compared to cases when water-based drilling fluids are used, fewer wellbore stability problems occur while drilling when invert emulsions (IEF) are used. In this paper, the theory of shale interaction with invert emulsions focusing on osmotic pressure and membrane efficiency is briefly reviewed.

Actual measurements of changes in shale strength of two very different shales have recently been directly made using a new test device from the University of Oklahoma: one from a deepwater environment and the other a more competent shale cored in a land-drilling operation. These shales were exposed to invert emulsions having different water phase activities, and the stresses required to cause failure in the samples were directly measured at different confining pressures. The results showed use of invert emulsions under some conditions weakened the shales, while under other conditions, the shales were strengthened. Elastic and porochemoelastic modeling efforts are then used to qualitatively corroborate observed shale strength changes seen in the laboratory.

ARMA 09-185

Borehole Stability Simulations of an HPHT Field Using Nisotropic Shale Modeling

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ABSTRACT: Most borehole stability problems occur during drilling in the overburden shale and mudstone. Typically borehole instabilities are associated with high pore pressures just above the hydrocarbon reservoir. Worldwide there is a tendency going towards deeper HPHT reservoirs with increased pressure and temperature. Consequently the drilling window margins are reduced and more emphasis is put on the borehole stability predictions. In order to prevent water influx the mud weight is kept above pore pressure and the collapse pressure. Further to avoid fracturing and tensile cracks the mud weight is kept below the fracture gradient. In order to predict the upper and lower limits for mud weight densities a proper description of the formation is needed. It is well known that the shale exhibits anisotropic behaviour due to sedimentation processes. The anisotropy is apparent both with respect to deformation and strength.

This paper presents the borehole stability simulations carried out for an HPHT field offshore Norway. An anisotropic shale model is implemented and calibrated against laboratory test results. Both drained and partially undrained stress paths are compared. In total three triaxial tests with different sample orientations are required to fully describe the anisotropic properties. The borehole stability calculations are carried out in the finite element code Abaqus, where the anisotropic model is implemented as a user routine. The simulation results are presented for different borehole inclinations, where emphasis is put on predicting the allowable underpressure.

ARMA 09-106

Borehole Failure Related to Bedding Plane

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ABSTRACT: This paper presents a model for the "plane of weakness" theory applied to a deviated borehole that penetrated laminated shale contains numerous bedding parallel weakness planes. Two conditions determine whether the rock fails along a weakness plane: the relative magnitude of the two normal stresses, and the angle between the borehole and the bedding plane. The model is applied to a deviated well that penetrated a tight fold in the northeastern British Columbia foothills belt in Canada. The well was associated with severe borehole failure prior to this geomechanical study. Subsequent drilling operations utilizing results of this study lead to a successful completion of the project.

SESSION 9: LAB CHARACTERIZATION: FLOW AND DYNAMICS

ARMA 09-045

Characterizing Internal Macropores Using Cross-Specimen Acoustic Tomography: Verification of Two Dimensional Results

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ABSTRACT: The engineering properties of a geologic material are greatly affected by the presence of macropores. Previous research has demonstrated that the size, location, and proximity of macropores influences both the strength and stiffness of specimens. Knowledge of the distribution of macropores in a specimen prior to testing would be useful for a number of reasons. We are currently developing a non-destructive method called cross-specimen acoustic tomography (CSAT) to determine the number, location, and size of the macropores in a laboratory specimen. The CSAT method uses a set of piezoelectric sensors that generate and receive high frequency acoustic waves. We measure the travel times of the acoustic waves through a specimen and then use a commercially available tomography software package to invert the data. The inverted velocity model is in turn used to locate the voids within the specimen. The verification of two dimensional (cross-sectional) results from plaster specimens containing large macropores of Styrofoam show the technique is promising and worthy of further development.

ARMA 09-139

Mechanical Properties of High and Lower Porosity Outcrop Chalk at Various Wetting States

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ABSTRACT: In order to study the influence of different wetting states on the mechanical properties of chalk, tests on both high porosity (45-49 %) and lower porosity (37-40 %) outcrop chalks had been conducted. The initial water saturation for the chalk cores was low. The cores were flooded with oil with different acid numbers and aged at reservoir temperature following a procedure designed to achieve a pre-determined wetting condition. The prepared cores were mounted in triaxial loading cells at reservoir temperatures in order to investigate mechanical parameters. Two types of fluids such as formation brine and synthetic seawater were flooded through the cores during the experiments. The results revealed that intermediate-wet cores were stronger than preferential and completely water-wet cores. The mechanical strength of chalk at various wetting conditions might be attributed to: (1) acid number of oils and the effect of oil films close to the intergranular contacts and/or (2) chalk dissolution and precipitation processes.

ARMA 09-157

Permeability Changes Due to Shear Dilatancy in Uncemented Sands

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ABSTRACT: Steam injection for heavy oil recovery increases the pore pressure and temperature of the reservoir, which can lead to shear failure in unconsolidated sands. Volumetric dilation from this type of failure can cause a permeability increase related to the stress path, compaction state, and grain mineralogy, size and shape. In this study, triaxial compression and radial extension tests were carried out on sand samples with different grain size distributions and initial porosities. The finer grained sands had smaller initial permeabilities than the coarser grained samples, but the finer grained samples showed the greatest permeability increase during shear dilatancy. Radial extension tests showed a maximum permeability improvement of 42% for fine grained sands. Under the same loading conditions, a similarly prepared coarse grained sample peaked at 10% permeability increase after 5% axial strain, but had a 10% permeability decrease for 10% axial strain. A permeability enhancement of only 12% was observed for triaxial deformation of the fine grained sand at 50 psi confining stress, and a confining stress of 200 psi inhibited permeability increase for the triaxial compression test, even though the volumetric strain was still dilatant.

ARMA 09-150

Evolution of Shear Strength and Permeability during Shear-holding in a Simulated Rock Fracture under Moderate Stress and Room Temperature Condition

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ABSTRACT: This paper presents direct shear test results for single jointed granite and mortar specimens to investigate effects of long-term load holding on mechanical and hydrological properties of rock joints. From the test results, it was confirmed that shear strength increased and permeability decreased for mortar specimens through three days load holding. For granite specimens, however, significant change was not observed on mechanical and hydrological properties even after the twenty-day load holding, which is likely due to low confining pressure relative to the strength of granite and insufficient load holding period.

ARMA 09-179

Measuring Static and Dynamic Moduli as Functions of Stress for a Weak Sandstone

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ABSTRACT: Laboratory measurements of static and dynamic moduli, in order to establish relations between these moduli as functions of stress, involves several challenges for the measuring techniques and for interpretation of the results. Different techniques for measurements of strain are seen to give significantly different results, and it is not obvious which technique is giving the most reliable results for this application. The uniaxial compaction modulus can be measured directly both by static and dynamic techniques, and therefore represents the most reliable comparison between static and dynamic moduli. For other moduli, such as Young's modulus and the bulk modulus, a comparison requires employment of assumptions regarding symmetry, or alternatively, extension of the measurement procedure by adding P-wave velocity measurements at an oblique angle. The results show that the relations between static and dynamic moduli are sensitive to the stress path and the location of the failure envelope.

SESSION 10: ROCK MASS CHARACTERIZATION I: SLOPE STABILITY, DESIGN AND ANALYSIS

ARMA 09-085

A New Method for Three-Dimensional Slope Stability Analysis—The Vector Sum Analysis Method

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ABSTRACT: Based on the fact that the force is a vector, a new method for slope stability analysis is proposed, called Vector Sum Analysis Method (VSAM). In this method, the stability analysis is done on the basis of the current stress state of slope and its whole potential sliding direction. Without excessive assumptions, the stability safety factor of slope can be obtained with this method and is called safety factor of VSAM. It is defined as the ratio of projection value of vector sum of ultimate anti-sliding capability to that of current mobilized forces to the whole potential sliding direction, and the key problem is the determination of whole potential sliding direction, which depends on the distribution of maximum anti-sliding shear forces on the potential slip surface. At the end of this paper, two classical examples of 3D slope are used to verify this method. The calculation results show that the safety factors of VSAM are well comparable to that of Limit Equilibrium Method (LEM). There has been a successful attempt about the application of VSAM in 2D slope stability analysis. So it is natural to extend it to three-dimensional analysis. Compared with the traditional methods of 3D slope stability analysis, the new method has two advantages: One is that there is a definite physical meaning and simple calculation, which is especially simple for 3D slope analysis. And the other one is that the safety factor is obtained through the current stress state without excessive assumptions unlike that of LEM and Strength Reduction Method (SRM). So, the application of this new method has a good future.

ARMA 09-149

A Numerical Investigation of Scale Effects on the Behavior of Discontinuous Rock

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ABSTRACT: In numerical simulations of mining induced problems, it is not possible to represent discontinuities at all length scales. However, all length scales are coupled, so the homogenisation process and the selection of what discontinuities must be represented explicitly should be rigorous. To investigate some homogenisation concepts for mine problems, the load-deformation response of some discontinuous rock masses at an example mine have been simulated using Explicit, Finite Element models. The intent of the analysis was to investigate the effects of specimen size and confining stress on strength, dilation and comminution. The analysis is used as a basis for a discussion of some preliminary ideas and concepts for deciding what length scale of structures need to be included in numerical models of mining deformation.

ARMA 09-184

In Situ Large Size Non Conventional Shear Tests for the Mechanical Characterization of a Bimrock in the Santa Barbara Open Pit Mine (Italy)

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ABSTRACT: A high mine slope in the disused Santa Barbara open pit mine (Tuscany, Italy) is cut in the Shale-Limestone Chaotic Complex (SLCC), which is a typical bimrock made up of a scaly-fabric clayey matrix including heterometric calcareous blocks. The slope shows evidence of instability phenomena: mainly rotational landslides and toppling countercracks. In order to characterize the mechanical behaviour of the SLCC bimrock, in situ large size non conventional shear tests were performed. The aim of in situ tests is to overcome the size limitation of laboratory specimens and namely to take into account the influence of calcareous blocks on the strength of the bimrock. Bimrock's strength parameters under natural conditions can be evaluated by means of a limit-equilibrium analysis taking into account shear test data and the geometry of the sliding surface.

ARMA 09-126

Is Thermal Fatigue a Possible Mechanism for Failures of Some Rock Slopes in Rio De Janeiro, Brazil?

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ABSTRACT: It has been observed along the years that a number of failures in rock slopes in areas of Rio de Janeiro, Brazil occurs in relatively dry periods when little, if any, rain fell. The present paper describes these events and proposes possible mechanisms for their occurrence. It is believed that daily fluctuations in temperature may create thermally induced stresses of magnitude enough to propagate cracks already existing in the rock mass. The paper presents data obtained from laboratory experiments and numerical analysis to verify the proposed mechanisms.

SESSION 11: LAB CHARACTERIZATION OF MECHANICAL RESPONSE: CREEP AND PORO-MECHANICS

ARMA 09-044

Strength and Failure Mode as a Function of Macropore Spacing: Experimental and Numerical Investigation

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ABSTRACT: Engineering properties of rock have been shown to be influenced by defects including porosity (Talesnick et al.,2001, Avar et al., 2003, Gates, 2008). Strength and stiffness of rock is affected by macroporosity as demonstrated in previous studies (Avar et al., 2003, Gates, 2008, Al-Harthi et al., 1998). The quantified effects of macropore spacing on the unconfined compressive strength of synthetic rock analog material and the effect of macropore spacing on failure mode are described in this investigation. Fifty-four 4" cubic specimens made of HydrocalTM and Plaster of Paris were tested in unconfined compression for strength, and the failure mode was observed. The cubic specimens have cylindrical voids extending from the front of the specimen through the back. The laboratory results are used as validation of 2D numerical simulation of unconfined compression testing of square specimens with circular holes. Strength data appear to fall between two bounds: an upper bound that displays increasing specimen strength as distance between macropores increases, and a lower bound that suggests decreasing strength followed by increasing strength as distance between macropores increases. There is also a trend observed in the failure mode of specimens, showing that as macropore spacing increases, the failure mode changes from tensile cracking to tensile cracking accompanied by shear failure. At the minimum macropore spacing the macropores act as a single "mega-macropore" and at maximum macropore spacing peak strengths are relatively high and specimens fail as macopores react to loading individualy.

ARMA 09-028

Experimental Study of Dissolving Effect on Mechanical Characteristics of Rock Salt

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ABSTRACT: Through a serial of rock salt uniaxial compression meso-mechanics experiments considering coupled stress-dissolving effect, the differences of mechanical properties of rock salt with/without the dissolving effect have been explored. Based on the result of experiments, the rule that mechanical property of rock salt has been changed under the dissolving effect has been proved; the mechanism of variation of mechanical property of rock salt on dissolving effect is hat the critical stress intensity factor of crack of rock salt has been decreased; the relationship between axial stress and dissolving time on dissolving phase, under the condition of different situation of cracks of rock salt specimen, has been analyzed; the variation of mechanical properties on rock salt with dissolving effect can be described quantitatively with the expression between H and dissolving mass m, H is the ratio of the axial stress value before and after dissolving. The achieved results on this paper can provide a foundation for the further analyses of coupled stress-dissolving mechanism of rock salt.

ARMA 09-095

Advances in Researches of the Mechanical Behaviors of Deep Bedded Salt Rocks in China

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ABSTRACT: Salt rocks are commonly utilized as the geologic host rocks for storage of gas and crude oil, and are also being considered for the disposal of radioactive waste due to its low porosity and permeability, self-recovering damage and better plastic deformation ability. The advances in researches of the mechanical behaviors of deep bedded salt rocks in China are reviewed comprehensively.

The engineering mechanical properties of bedded salt rocks were investigated for the purpose of the energy storage in deep bedded salt rocks formation. The compression tests showed that the presence of anhydrite interlayer affects strongly the deformation and failure characteristics of bedded salt rocks. A 'stress drop' phenomenon of stress-strain curves was observed for the low confining pressure cases, denoting the anhydrite layer fractures prior to salt rock. The creep tests on salt rock, anhydrite and composite rock samples implied that the steady-state creep ratio of interlayer was one order lower than that of the salt rock. The creep deformation of surrounding rocks of storage cavern will be controlled by the salt rock layer, while the anhydrite layers will restrict the long-term volume shrinkage. For investigation the mechanical properties of the interfaces between anhydrite and salt rock, the direct shear tests, Brazilian disk tests and SEM tests were carried out. These experiments showed that the interfaces between anhydrite and salt rock are bonded perfectly and are not a weak one as expected. This unique property of the bedded salt rocks would benefit greatly the sealability and stability of the energy storage caverns in bedded salt rocks. Finally, the Cosserat-like medium constitutive theory and its applications to the stability analysis of the salt caverns in bedded salt rock formation were introduced.

ARMA 09-043

Undrained Poroelastic Response of Berea Sandstone and Indiana Limestone to Confining and Deviatoric Stress Change

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ABSTRACT: In this study we have measured the undrained pore pressure response of Berea sandstone and Indiana limestone in response to changes in mean and deviatoric stresses. In particular, we have performed tests up to a confining pressure of 70 MPa and differential stress raging from 0 to 150 MPa. For Berea SS, the pore pressure responded to confining pressure (also mean stress because there was no differential loading) in the usual manner corresponding to $\Delta p = B\Delta\sigma m$, with B ranging from 0.3 to 0.55. Similarly, for Indiana limestone, B was measured to be 0.15 to 0.46. On the other hand, when the mean and deviatoric stresses were both increased during the test, a B in the range of 0.37 to -0.55 was measure for the Berea sandstone. This reduction in pore pressure increase with deviatoric loading, is suggestive of volumetric deformation under deviatoric loading. At high deviatoric stress levels and undrained conditions, the pore pressure response consists of both elastic and inelastic volumetric strain. For Indiana Limestone, the pore pressure was measured before and after failure. Skempton factor A and B values for different confining pressure and differential axial loadings in elastic and post peak regions for Indiana Limestone also have been measured. After yielding, the inelastic response was eliminated by repeated stress cycling, to capture the reversible elastic component. The sensitivity of pore pressure to deviatoric stress measured at constant confining pressure was found to decrease with increasing deviatoric stress level resulting in a smaller value for A.

ARMA 09-118

Experimental Investigation of the Effective Stress Coefficient for Various High Porosity Outcrop Chalks

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ABSTRACT: The contribution of the pore fluid pressure to the reduction of the effective stress during loading of fully saturated high porosity chalk (>40% porosity) has often been assumed to be represented by an effective stress coefficient close to unity. This assumption entails that the differential stress, which is the difference between the total stress and the pore fluid pressure, is equal to the stress the rock matrix is exposed to. Laboratory experiments were conducted by simultaneously increasing total stress and pore pressure. These tests resulted in substantial strains that should not occur if the assumption of an effective stress coefficient close to unity was true. Different explanations for these strains are discussed, among these consolidation effects, partial saturation effects, microscale damage, and possible laboratory equipment effects. The strains that were observed during the test phase mentioned above led to the initiation of a subsequent study focusing on the effective stress coefficient for porous chalk material. The results from this study suggest that the effective stress coefficient for high porosity outcrop chalks depends on the applied stress and the pore fluid, and is not a constant, nor close to unity as commonly presumed.

ARMA 09-136

Research on Factors Influencing Characteristics Experimentation and Mechanism of Rheological Parameters of Soft-soil

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ABSTRACT: Soft-soil has obvious rheology character, it will induce subsidence distortion, landslide etc serious geotechnical engineering and geologic disasters, and make severe threaten to stability and security of projects. The initializing shear stress and viscosity of sullage soft-soil are tested under static load, and the influencing characteristics are analyzed of which the percentage of clay and water affect the rheological parameters. The mechanism of which the percentage of clay and water affect the rheological parameters are opened out by using the theory analysis and technology of structure micrograph. The research results have have theoretic and practical significance for us to analyse changing disciplinarian of rheological parameters, reinforce softsoil foundation, raise bearing capacity and whole strengthen of soft-soil.

SESSION 12: ROCK MASS CHARACTERIZATION II: DAMS AND HIGH-WALLS

ARMA 09-074

Evaluating Rock Mass Deformability Characteristics Using Rigid Plate Load Test in Bakhtiary Dam Investigation

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ABSTRACT: In sensitive projects such as large dams, estimation and evaluation of rock mass deformability parameters is an important component of the field studies. Over the years, various methods have been used for estimation of rock mass deformability, including in-situ rock mechanics tests. Bakhtiary dam and Hydro Power Plant in Iran which is under study at the present would be the highest double curvature concrete dam in the world with the height of 315 meters. Obviously, evaluation of the reaction of the dam foundation and potential ground deformation under the heavy loading is even more sensitive for this project. Various in-situ tests for defining rock mass deformability parameters have been used for this project. This includes Dilatometer test (DL), Extra Large Flat Jack Test (LFJ), and Plate Load Test (PLT). In this paper, these methods are compared and PLT tests are discussed in more details. Results of 41 performed PLT tests are evaluated using ASTM and ISRM formulas as well as Unal method. It seems like the result of Unal analysis is more consistent and reliable.

ARMA 09-083

Laterally Controlled Shear Testing of 1:200 Scale Model Gravity Dam Monoliths over a Foundation with Three-Dimensional Interfacial Roughness

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ABSTRACT: A suite of shear tests was performed on a set of scale model monoliths to investigate the influence of macroscopic, three-dimensional, foundation roughness on shear strength. Two of the monoliths were designated "critical" blocks, and sheared over the model foundation under a variety of lateral boundary conditions, with the remaining monoliths providing lateral confinement. The lateral boundary conditions included: 1. No lateral constraint; 2. One-sided lateral constraint; 3. Loose two-sided constraint and; 4. Rigid two-sided constraint. The resulting differences in configurational shear strengths, closely related to the unconstrained sliding trajectories and parameterized by the "effective" friction angle of each block, are used to highlight the reinforcing action of lateral confinement over asymmetric sliding topography. It is shown that the opposing unconstrained trajectories of the critical monoliths promote the formation of a kinematic wedge, whose effect on the overall stability of the model dam is evaluated numerically.

ARMA 09-072

Study on the Deformation Response of a Water Inlet High Rock Slope Excavation in a Large Hydroelectric Station in Southwest of China

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ABSTRACT: The excavation and stability of the hectometers high rock slope are currently an important technical problem of the water conservancy project construction. Through the abundant geological investigation of construction tracing in situ-site, the water inlet slope with vertical height of 106m in a large Hydroelectric Station in southwest of China. Through systematical study, the basic laws and special characteristics of its deformation responses are acquired and classified as follows: 1) During the slope excavation, there is strong synchronism between the slope deformation and its excavation process. 2) The slope deformation is mainly influenced by excavation. 3) The slope deformation generally is weakening with the distance between the excavation plane and the monitoring position, whose responding features of ultimate stability have three stages, that is, rapid increase stage of deformation, slow enhancing stage and the stable stage. 4) The high slope deformation can be classified into 3 types, the shallow surface relaxation, the harmonized gradual change and rebound fluctuation. The main one is the shallow surface relaxation.

ARMA 09-050

Foundation Investigations for Refurbishment Cut-off Walls at Arapuni Dam, New Zealand

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ABSTRACT: Arapuni Dam, a 64 m high curved concrete gravity structure founded on Quaternary-age ignimbrites, has experienced several seepage flow incidents since its construction between 1925 and 1927. After grouting of the latest flow in 2001, the longer-term future performance of the dam was investigated by triple-tube coring of the foundations, laboratory strength testing, weir and piezometer monitoring of responses to induced changes in pressures in the foundations, and characterization of water chemistry and isotope signatures as well as temperature. The paper describes the use of these techniques to identify four subvertical zones (fissures) controlling the pattern of foundation seepage along joints formed in the Ongatiti Ignimbrite, many of which were either open or infilled with erodible nontronite clay. Recognition of the four fissure zones has enabled the design and construction of four discrete 90 m high cut-off walls through the dam and into its foundations, rather than treatment across the whole dam foundation.

ARMA 09-101

Repair of the Pi'ilani/Hana Arches, Pi'ilani Highway, Maui, Hawaii

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ABSTRACT: The Pi'ilani/Hana Arches are three historic stacked rock walls constructed above natural rock arches. The walls were designed to retain and support the Pi'ilani Highway above the Pacific Ocean near Kipahulu on the southeast coast of the Island of Maui. An earthquake, on October 15, 2006, damaged the arch structures as loosened rock fell from beneath the highway, which undercut the foundation of the arches and jeopardized their stability. The County of Maui subsequently closed the highway because of the rockfall danger and issued a contract to repair and stabilize the road and slope beneath the arches. Stabilization of the rock slope beneath the arches required scaling techniques to remove the loose rock and debris followed by application of an initial blanket of reinforced shotcrete to control rockfall and support of the roadway. Once the shotcrete wall cured, a pattern of rock dowels, and drains was installed and overlapped with a final layer of reinforced dyed shotcrete. The stabilization project cost $1.8 million and was funded primarily through FEMA dollars; included about 35 cubic meters of scaled rock and debris, 640 lineal meters of rock anchors, and 172 cubic meters of shotcrete. The project was completed in a record 2.5 months from late September through early December 2007.

SESSION 13: UNDERGROUND GEOMECHANICS MODELING

ARMA 09-200

Effect of Stope Undercutting on its Wall Overbreak

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ABSTRACT: Ore dilution or stope overbreak increases the cost of production and ultimately reduces the profitability of a mining operation. The adverse economic impact of ore dilution is due to the added costs associated with the mucking, haulage, crushing, hoisting, milling, and treatment of waste rock or low grade ore in the hangingwall and footwall. One factor that could have a significant influence on stope overbreak is the undercutting of the stope into the walls. Undercutting stope walls is often necessary, in particular in narrow vein mines. This paper presents a numerical model parametric study to examine the influence of stope undercutting on its wall overbreak using geomechanical data from the Lapa mine of Agnico Eagle Mines Limited.

ARMA 09-202

3-Dimensional Numerical Modelling of Stope Sequencing for Mine Planning

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ABSTRACT: There are many inherent risks in creating a mine plan for a new ore zone in an underground mine; one of such risks is the redistribution of stresses that could be a cause for concern of instability. Numerical modelling has been increasingly used as a powerful tool for the assessment of mine plans from a geomechanics perspective. Using numerical modelling tools, it is possible to model the planned stope extraction sequence and evaluate the influence of mining induced stresses on the stability of remnant pillars, and use this information to remedy potential setbacks.

This paper demonstrates this approach through a case study of the short-term mine plan of the Lapa mine of Agnico-Eagle Mines Ltd., an underground gold mining operation located near Val d'Or, Quebec, Canada. Three-dimensional elasto-plastic modelling is used to compute mining-induced stresses and the extent of yielding in a remnant pillar, which is created by the stope extraction sequence as planned with a longitudinal retreat mining method.

ARMA 09-137

Utilizing Convergence Reading to Determine Stability and Support Category in NATM Tunneling at the Devil's Slide Tunnel

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ABSTRACT: The Devil's Slide Tunnel project, located south of San Francisco along Highway 1, consists of twin bore tunnels approximately 1250 meters long. The tunnels are currently being excavated and supported utilizing the "New Austrian Tunneling Method" (NATM). At Devil's Slide a daily decision is made on ground support category based on the rock behavior determined by geology, ground water conditions, and over burden. As the excavation progresses, convergence arrays are installed to measure and quantify the ground movement. The convergence readings permit the original support category determination to be validated to calibrate the NATM category support determination process. The convergence readings also allow the stability of the tunnel to be evaluated so that additional measures can be taken if necessary. This paper will present some of the

convergence readings to date from the Devil's Slide Tunnel. This paper will discuss how the convergence readings have been used to calibrate the NATM category support determination process and how they relate to the use of local ground support measures. A brief discussion of lessons learned will also be given.

ARMA 09-152

Hydromechanical Evolution and Self-Sealing of Damage Zones around a Microtunnel in a Claystone Formation of the Swiss Jura Mountains

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ABSTRACT: The damage zones around cylindrical excavations such as seal sections in tunnels or shafts have been subjected to extensive experimental and theoretical investigations in the field of underground waste disposal. Conceptual and numerical models have been developed to describe the hydromechanical processes associated with the creation and evolution of damage zones during the operational phase and after back-filling of the underground structures. However, only little data from tunnel scale experiments is available for comprehensive validation of the EDZ models. This paper describes a large-scale experiment on hydromechanical processes around underground structures as part of a long-term geoscientific research program at the Mont Terri Underground Rock Laboratory in the Jura Mountains of Switzerland. A horizontal microtunnel with a diameter of 1m and a length of 13m was drilled in an overconsolidated claystone formation. The rock around the microtunnel was monitored before and during excavation. After installing monitoring instruments in the open tunnel, the end of the tunnel was backfilled with sand (test section) and a large hydraulic packer was emplaced in the seal section. The packer was inflated and subsequently the test interval was saturated with a synthetic pore-water. Following saturation an extended program of hydraulic testing was performed. The paper presents data, interpretation and modeling of the hydraulic testing where both water pressure and stress in the seal section have been controlled to investigate the ongoing self-sealing of the damage zone and the hydro-mechanical response of the system under different effective stress conditions.

ARMA 09-014

Study on Application of Displacement Measurement Method in 3-D Physical Model Tests of Cavern Complex

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ABSTRACT: Using the Shuangjiangkou hydropower station on the Dadu River in China as a background, another new physical model test of an underground cavern complex in a true 3-D stress state has been conducted based on a quasi-three dimensional model test which was performed in 2007. The original experimental techniques used in last model test have been significantly developed, and some new measuring techniques have been implemented in the new model test. In order to solve the problem in measurement of small displacements in the surrounding rock masses, the digital speckle correlation method (DSCM) and special displacement sensing bars based on fiber Bragg grating (FBG) technology are adopted. Mini multi-point extensometers

with high-precision grating scales are developed as transducers for displacement monitoring. We also conducted a numerical simulation with almost the same conditions, and compared the results of the model test and the numerical approaches. The study shows that the research and application of the displacement measurement methods used in the surrounding rock masses for large-scale model tests of cavern complex under 3-D stress field have achieved satisfactory results.

ARMA 09-061

LaModel Analysis of the Crandall Canyon Mine Collapse

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ABSTRACT: On August 6th, 2007, the Crandall Canyon Mine in Utah collapsed entrapping six miners. It appeared that a half square mile area of pillars in the western section of the mine had bumped in a brief time period, filling the mine entries with coal and entrapping the six miners working there. Ten days later, during the heroic rescue effort, another bump occurred thereby killing three of the rescue workers and injuring six others. This paper details a back-analysis of the August 6th, 2007 collapse using the LaModel boundary-element program along with the best available geotechnical information. For the back-analysis, an initial model of a previous bump at the mine was used to calibrate the input rock mass, coal and gob properties. Then, the calibrated input was used to model the mining scenario at the time of the collapse. Ultimately, it was determined that the fundamental cause of the collapse was the large area of equal size pillars with near unity safety factors in the collapse area. It is hoped that the enhanced understanding of the collapse presented in this back analysis will foster improvements in future mine designs to eliminate similar type events.

SESSION 14: CONSTITUTIVE MODELS OF ROCK DEFORMATION

ARMA 09-035

Hydromechanics of a Virtual Rock Core

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ABSTRACT: In this study, numerical tests of hydromechanics were conducted on a virtual rock core. A series of 2D digital images is captured through X-ray CT scanning of the rock sample. Each 2D CT image is then processed to ascribe a map of pixel values. The map of pixel values is thresholded to relate pore density that defines grain or pore to porosity. The same number of 2D CT images that represent the porosity distribution (map) are then used to construct the 3D virtual rock core. Through interpretations, the porosity for each voxel within the virtual rock core is defined. Through these steps, a 3D porosity map within the virtual rock core was created. Maps of other physical properties such as elastic modulus and permeability were produced through their empirical relations with the porosity. These property maps were used as direct inputs for the hydromechanical numerical tests. The numerical experiments are completed through the development and application of a porosity-based finite element hydro-mechanical model. In this hydromechanical model, the porosity changes with the volumetric strain and pore pressure. Because both elastic modulus and permeability are defined as a function of porosity, all these three important

physical properties change with time. Results from these numerical tests demonstrate the impacts of rock heterogeneity on the hydromechanical performance (without considering the heterogeneity, the fluid flux could be overestimated by 130%). Through comparing the results from numerical experiments with those of the ideal homogeneous rocks, these heterogeneous impacts were quantified.

ARMA 09-111

Damage Rheological Model with Non-Stationary Parameters and its Engineering Application

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ABSTRACT: The mechanical parameters of a rheological constitutive model for rock are usually assumed constant, and all the mechanical parameters of rock masses are considered unchangeable with time. Actually, under the effect of geotectonic movement, groundwater seepage, natural weathering and many other factors, the mechanical parameters of rock masses vary obviously with time. In this paper, the deterioration effect of the rock parameters is considered and a damage rheological constitutive model with non-stationary parameters is established. In this model, the rheological parameters of the rock deteriorate gradually. The non-stationary rheological parameters reflect the deterioration process of the material properties directly. This model is applied in a slope design for a dam foundation at a hydropower station. Damage rheological stability of the slope during excavation is evaluated. It shows that when damage rheology is considered, the displacement is larger compared with the case of ignoring damage rheology, and the most remarkable percentage increase reaches 12%. The study shows that the deterioration effect of the rock parameters is of full importance for the project design and construction safety.

ARMA 09-024

Physical and Numerical Investigation of a Cemented Granular Assembly under Uniaxial and Triaxial Compression

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ABSTRACT: This paper firstly presents a review on applications of DEM in rock mechanics, with particular focus on similitude studies between DEM and physical experiments. A challenge in DEM simulations is to select appropriate micro-mechanical models (and parameters) to recover the observed macro-mechanical behavior. An ideal experiment would validate DEM simulations against identical physical models with similar micro-mechanical properties. The second part of the paper discusses the results of such investigations undertaken on numerical and physical cemented (cohesive) assemblies in uniaxial and triaxial compression. Physical samples were prepared using steel balls bonded with Portland cement, cured under controlled laboratory conditions and tested in uniaxial and triaxial compression. Uniaxial tests results were analyzed to characterize the damage thresholds with the help of acoustic emission and volumetric strain monitoring. Numerical simulations were conducted with PFC3D using known and derived micro mechanical parameters from physical testing. The results from both numerical and physical tests showed good correspondence in macroscopic behavior i.e. peak strength, stages of damage, mode of failures. However the numerical simulations reflected a stiffer mechanical response than physical assemblies.

ARMA 09-058

Evaluation of the Strength of a Rock Mass Considering the Critical Strain of the Intact Rock by a Homogenization Method

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ABSTRACT: In this paper, we present an evaluation method for the strength of a discontinuous rock mass considering the critical strain of the intact rock. This method, which incorporates a weak layer model that describes the mechanical behavior of cracks, is based on a mathematical homogenization theory. The basic idea of this method is that the failure criterion for the rock mass is estimated by the critical strain of the intact rock. To express the critical strain under the state of three dimensions, the evaluation equation for the critical strain, which has conventionally been expressed by the axial strain, is transformed to an equation for the critical strain which is represented by the second invariant of the deviator strain. The strength of the rock mass is evaluated by numerical tests that use a localization process through a homogenization theory. Localization is a process that calculates the macroscopic stress as the response of the model to the forced macroscopic strain. A numerical analysis of in situ rock mass tests for a discontinuous rock mass was carried out using this method. The shear strength conformed to the strength obtained by the insitu tests, and therefore, this method can be used to evaluate the strength of a rock mass.

ARMA 09-081

Anhydrite Behavior in a Salt Formation: WIPP Applications

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ABSTRACT: The behavior of anhydrite layers deforming in a bedded salt medium is examined. Applications of structural analyses for the Waste Isolation Pilot Plant include rock mechanics calculations of room closure and porosity surfaces for performance assessment. The calculation scheme includes salt creep and large-strain deformation involved in room closure. Salt crystal plasticity is well established and room-closure calculations have reasonably approximated full-scale measurements during the experimental phase and continue to adequately predict closure after ten years of operational experience. Natural bedded salt formations comprise sequences of anhydrite stringers which are stiffer and stronger than salt. The rheological contrast gives rise to combinations of fracture and deformation features of both the salt and the anhydrite. Although room closure is dominated by salt deformation, the physical and mechanical properties of anhydrite stringers above and below the disposal horizon have important performance implications. Finite element analyses of anhydrite shear failure within the creeping salt medium are augmented with photographic observations from the microscopic scale to the field scale. These results are put in context with a wealth of anhydrite laboratory data and relevant field test observations. This information adds significantly to analyses of mechanical behavior of anhydrite deformation in a creeping salt medium.

ARMA 09-021

Reliability Assessment of Hoek-Brown Rock Mass Stability

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ABSTRACT: This paper presents a new method to implement reliability analysis of rock mass stability directly starting with the basic variables of Hoek-Brown empirical formulas. Firstly, the subjectivity and limitation of the disturbance factor, evaluated according to the guidelines suggested by Hoek et al (2002), are discussed, and the quantitative assessment of the disturbance factor with elastic longitudinal wave velocity is recommended. Secondly, based on the safety factor of elements in rock mass, a performance function containing the basic variables of Hoek-Brown empirical formulas is set up. Thirdly, the Rosenbleuth point estimate method is chosen to estimate the mean and standard deviation of the safety factor, and the process to calculate the reliability index of rock mass stability, based on the combination of the Rosenbleuth point estimate and finite element methods, is described in detail. Finally, the stability reliability of a certain cutting slope is computed and analyzed, and the computational result is consistent with the features of the rock mass failure occurred. The recommended method in this paper could be conveniently used to assess the stability reliability of slopes, foundations and underground averns related to rock mass.

SESSION 15: FLUID-COUPLED MECHANISMS AND TRANSPORT

ARMA 09-033

Modeling Fluid Mixture Transport and Cross-Flow in Layered Media

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ABSTRACT: Coupled convection-dominated transport equations are presented to evaluate particle deposition and cross-flow in layered formations when the flow stream is injected (produced) into (from) two layers with different matrix permeabilities. The governing equations are presented in a cylindrical coordinate system. Particle deposition/capture is simulated as a temporal retarding process and cross-flow is assessed by the concentration difference at the interface of the two contrasting layers. The solutions for concentration in each layer are obtained using Laplace transformation and the related numerical inversion. Parametric sensitivity analyses reveal that the degree of retardation appears to have a controlling effect on the fluid mixture transport process, and the effect of cross-flow can become more significant if either the dispersion coefficient becomes substantially larger, or the concentration difference between the two contrasting layers becomes much more significant.

ARMA 09-156

Water Imbibition in Oilfield Rocks and Applications to Oil Recovery

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ABSTRACT: Understanding the potential of spontaneous imbibition of water based fluids to reservoir rocks is of high interest to the oil industry. Imbibition affects the way water displaces hydrocarbons through the reservoir pore system, for example during water flooding, and defines the sweeping efficiency of secondary recovery operations. In unconventional gas reservoirs, large surface area is required for economic production. This is created via hydraulic fracturing. Understanding the effect of spontaneous imbibition of fracturing fluids to the rock matrix, even when small, is essential to gas production from these reservoirs. In this work, we measured the spontaneous water imbibition on nine oilfield rocks (8 sandstones and a limestone), and evaluate water suction capacity as a function of time. We also compare these measurements to water suction in capillary slides. Results indicate that the water imbibed is proportional to the rock porosity; however, the rate of imbibition is a function of wettability (termed by others the rock suction potential). We found that the mass of water imbibed and the fraction of the imbibed pore volume is proportional to the square root of time. This is in line with the one-dimensional theory of capillary suction. Different rocks have different slopes. In addition, small departures from the theory are found during the early and late

times. This is possibly due to boundary effects (small samples) and a departure from one-dimensional suction. We believe this information is of high importance to the oil industry for applications of water flooding, enhanced hydrocarbon, for it is easier to displace hydrocarbons from reservoir rocks with higher water imbibition potential. It is also of high importance for hydraulic fracturing of unconventional gas reservoirs.

ARMA 09-201

Analysis of Hydromechanical Well Tests in Fractured Sedimentary Rock at the NAWC Site, New Jersey

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ABSTRACT: Hydromechanical well tests involve measuring and interpreting displacements along with hydraulic heads that result when a hydraulic stress is applied to a well. The motivation behind this type of test is that the displacement measurements provide information about the constitutive properties and structure of the aquifer that go beyond what can be derived from pressure signals alone. We used a borehole extensometer to measure transient displacements with a resolution of +/- 25 nm during well tests in fractured mudstone and sandstone at the former Naval Air Warfare Center in West Trenton, New Jersey. One well showed opening displacements on the order of 300nm during slug tests with maximum head changes of 7 m. Inversion of the transient signals suggest that a conductive fracture (aperture = 380 μm, normal stiffness = 8×108 Pa/m) was largely responsible for the pressure signal, but the displacement signal appears to have resulted from both the fracture and deformation of the enveloping sandstone (E = 5 GPa, permeability = 0.6 md). At another well, an anomalous but repeatable signal was characterized by closing displacements during increasing pressure. This displacement signal can be explained by a hydraulically active fracture below the extensometer that became pressurized and compressed the overly sediments. Poroelastic theoretical analyses were inverted to estimate parameters and verify interpretations.

ARMA 09-146

Modeling Methane Emissions and Ventilation Needs by Examination of Mining Induced Permeability Changes and Related Damage to Ventilation Controls

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ABSTRACT: Understanding methane emissions in underground coal mines is critical for a safe and productive mine. In addition to reasonable estimation of initial coalbed reservoir parameters, it is also crucial that changes in effective stress due to mining and pore pressure reduction are taken into account due to their effects on porosity and permeability. Primary parameters for estimation of emissions or modeling of the mining environment for this purpose are porosity and permeability which can change dramatically as a result of stress redistribution associated with mining and gas desorption from a large coal volume. These parameters affect the emission rates and ventilation requirements, as well as water inflow into the working environment. Stopping leakage, on the other hand, is a secondary stress dependent factor in estimation of emissions, as convergence of the roof and floor strata, compromising the integrity of the stopping, may result in leakage, making prediction of ventilation requirements difficult. This paper aims to examine the effects of porosity and permeability changes of the coal seam on methane emissions in an underground continuous miner section. The models were developed and executed in a dynamic fashion to

simulate an advancing section. Through this process, the changes of effective stress in coal, particularly their change paths, on porosity and permeability were incorporated into the models and methane emissions, concentrations, air requirements, water inflow and possible leakage from the stoppings were investigated using a conventional coalbed methane reservoir model

SESSION 16: IN SITU STRESS MEASUREMENT TECHNIQUES

ARMA 09-088

Precise Minimum Horizontal Stress Determination from Pump-In/Flowback Tests with Drilling Mud

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ABSTRACT: StatoilHydro has implemented the pump-in/flowback test as the preferred way of performing an XLOT (extended leak-off test) with mud for minimum stress estimation. In this paper we briefly review our standard method as presented in previous publications. We provide new data supporting one of our main conclusions from previous work: traditional XLOTs tend to overestimate the stress in tight formations. Further, we show that the method is also very valuable in permeable formations, by presenting an example of how a very clear stress determination was possible from the flowback phase, while the interpretation from the shut-in phase in another test cycle was at best ambiguous. We further discuss the difference between topside and downhole data, focusing on the magnitude of friction during the various phases of a test. Next, we discuss some examples of flowback tests that did not give a credible minimum stress interpretation. Three circumstances are identified which may hinder stress estimation: 1) Unfavorable combination of well azimuth and inclination, 2) Poor integrity of the casing shoe, 3) Unfavorable fracture shape.

ARMA 09-003

Critical Review of Leak-Off Test as a Practice for Determination of In-Situ Stresses

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ABSTRACT: A precise estimation of the in-situ stress tensor is important for any underground excavation. It is particularly crucial in petroleum engineering when reservoir condition of pressure and temperature are usually high. Leak-off tests (LOT) are regularly performed in new wells where the formation characteristics have not been established yet. A number of technical communications have stated that leak-off test can be used for measuring the minimum in-situ stress magnitude, which is not completely correct due to the operational procedure itself and the inaccurate guidelines adopted for interpreting leak-off tests. The authors first performed critical reviews of the leak-off test and the extended leak-off test, and then studied the three-dimensional stress distribution around the bottom of the borehole. Instead of creating a vertical fracture which can be expected from the solution of an infinite borehole, leak-off test procedures may initiate a horizontal fracture along the bottom of the wellbore before the fracture turns in the direction according to the orientation of maximum principal stress prevailing in the reservoir.

ARMA 09-131

Development of Rock Stress Measurement Probe Based on The Pilot Hole Wall Deformation Method Laboratory Tests

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ABSTRACT: The theory and a prototype tool were developed for pilot hole wall deformation, measurement. This is a 3-dimensional stress measurement method based on the stress relief principle. A pilot hole is drilled from the bottom of a borehole and the stress measurement probe is inserted into the pilot hole. The differences between the displacements by the elastic stress analysis and those measured by using the probe were within 3% in the uniaxial compression test of an acrylic resin plate with a hole. The stress components which were applied to a cubic Kimachi sandstone specimen with an inclined borehole were evaluated by using the probe within an error of 6% relative to the applied maximum principal stress in a biaxial loading test.

ARMA 09-075

Mechanism Analysis and Preventive Methods for Rock Bursts in Deep Mining Conditions

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ABSTRACT: With the decrease of shallow mine resources, developing deep underground resources has become an inescapable reality in mining industries all over the world. However, deep underground mining is faced with many problems. The most distinct difficulty in deep underground mining is mining disturbance and " three high;" that is, high stress, high temperature and high pore water pressure. In addition, rock mechanics characteristics are very challenging and frequently cause increase of hazards, such as rock bursts, water invasion, and instability of goaf, all of which have high incidence rates and complex hazard mechanisms. This paper analyzes the rock burst mechanism theories, including strength theory, outburst proneness theory, energy theory, and instability theory. Main discriminations of rock burst include stress discrimination, energy discrimination, and lithology discrimination, among others. Rock burst is related with rock physical parameters (e.g., strain, stress, temperature, acoustic emission), so we can improve the forecast of rock bursts by researching changes of these parameters. With the goal of reducing the occurrence of rock bursts, this paper offers some preventive and control measures which are of greatest theoretical and practical significance to avoid rock-burst-related occurrences in the development of deep underground mining, to reduce the cost of mining under deep cover, and to improve overall economic efficiency.

ARMA 09-076

Evaluating the Present in-situ Stress-State for the Richton, MS, Strategic Petroleum Reserve Site Using Geomechanical Analyses

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ABSTRACT: The United States Strategic Petroleum Reserve has selected the Richton Mississippi (MS) salt dome as an oil storage site suitable to increase its current capacity to one billion barrels. In order to confirm that the Richton MS site is adequate for storage of oil deep underground, an evaluation of the present in-situ stress-state was investigated using numerical techniques involving large scale geomechanical analyses. Several Finite Element Analysis (FEA) models were constructed to approximate the complex three-dimensional Richton salt dome formation and surrounding rock in two-dimensions. These FEA models elucidated the significance of a parental salt bed which feeds the Richton salt diapir formation. Using complex creep material models to treat the near-field Richton salt diapir and elastic material models to simulate the surrounding media,

the structural response of the Richton salt dome was interrogated for several geometric configurations and initial conditions. Results of these FEA simulations showed a significant difference in vertical, horizontal, and von Mises in-situ stress states, which provide valuable information as to where the salt caverns might best be located within the dome to maximize structural integrity, etc.

SESSION 17: ROCK MASS CHARACTERIZATION III: ROCK MASS CLASSIFICATION, DEFORMATION, AND MONITORING

ARMA 09-171

Rock Slope Stability Analysis along the North Carolina Section of the Blue Ridge Parkway: Using a Geographic Information System (GIS) to Integrate Site Data and Digital Geologic Maps

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ABSTRACT: In 2008, the North Carolina Geological Survey (NCGS) completed a five-year geologic and geohazards inventory of the 406-km long North Carolina segment of the Blue Ridge Parkway (BRP). The ArcGISTM format deliverables for rock slopes include a slope movement and slope movement deposit database and maps and site-specific rock slope stability assessments at 158 locations. Database entries for known and potential rock slope failures include: location data, failure modes and dimensions, activity dates and levels, structural and lithologic data, the occurrence of sulfide minerals and acid-producing potential test results. Rock slope stability assessments include photographs of the rock cuts and show locations and orientations of rock data, seepage zones, and kinematic stability analyses. Assigned preliminary geologic hazard ratings of low, moderate and high indicate the generalized relative probability of rock fall and/or rock slide activity at a given location. Statistics compiled based on the database indicate some general patterns within the data. This information provides the National Park Service with tools that can aid in emergency preparedness, and in budgeting mitigation, maintenance and repair measures.

ARMA 09-019

Metamorphic Rock Mass Characterization using the Geological Strength Index (GSI)

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ABSTRACT: The Geological Strength Index (GSI) was introduced by Hoek et al (1994) as an alternative method to classify rock mass due to difficulties in applying the Bieniawski's Rock Mass Rating (RMR) to very poor rock masses. The GSI is an important tool to estimate parameters such as cohesion, friction angle and deformation modulus of rock masses. The author developed a new GSI table in 2000 to adapt the original GSI to metamorphic rock mass characterization in Venezuela. In 2007, the table was modified again to incorporate a non-foliated rocks structure column in order to include a broad range of metamorphic rock types. The experience in Venezuela in more than 2,000 classifications using the GSI table for metamorphic rocks, indicates an effective means to evaluate metamorphic rock mass in tunnels, slopes and foundations. In the last five years, the author has been working in the Blue Ridge and Piedmont Province areas of the Appalachian Mountains where metamorphic rocks such as schist, phyllite and gneiss are present. Similar characteristics between these rocks and metamorphic rocks in Venezuela allow the use of the modified GSI classification for metamorphic rock mass.

ARMA 09-114

Application of Real Time Monitoring System in Cut Slope Management System of Korea

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ABSTRACT: Korea has a network of 12,477km of national highways. In Korea, a number of cut slopes are necessarily created under road construction due to its mountainous topography. KICT (Korea Institute of Construction Technology) and the government MLTM (Ministry of Land, Transport and Maritime) have developed and operated CSMS (Cut slope management system) project in order to maintain the stability of cut slopes nationwide since Dec. of 1997. RTMS (Real Time Monitoring System) combining civil engineering and IT (information technology) was constructed for the monitoring of risky cut slopes and a method to remotely monitor them at office or by mobile communication was also developed. Furthermore, a disaster-preventive warning system combining CSMS and RTMS is operated to prevent any accident beforehand by giving notice to the public using the road as soon as any risk indication of cut slopes is detected.

ARMA 09-103

Monitoring and Computations on a Landslide in an Open Pit Mine

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ABSTRACT: The paper reports a monitoring and computation experience related to geotechnical evaluations on a landslide which developed in a sector of an open pit talc mine. The lithology, rock mass structure and groundwater conditions at the mine site are quite complex and their interaction with the open pit exploitation operations have triggered the landslide. As shown from topographic and inclinometric measurements obtained from the monitoring network, the failure prevailingly develops inside the loose and weathered, near surface, micaschist and likely consists of overlapping movement surfaces, of which one reaches a depth of 20m, but some sub-cm displacements also appear even after a depth of 50m. The results from FEM based SR analyses confirm the role of the different rock mass lithologies and fault zones and their strength on the landslide failure mechanism and size. The open pit slope scheme, although highly simplified, allows a suitable simulation to be made of the adverse effects of the groundwater level and of a further hypothesized lowering of the open pit toe on the development of the slope failure.

SESSION 18: FRACTURE INITIATION AND GROWTH – MIXING UP THE MODES

ARMA 09-056

Analysis of the KII Mode Shear Fracture Toughness for Brittle Materials

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ABSTRACT: Understanding failure mechanisms is important to the fields of mining, civil, and geology. Especially, a shear fracture propagating ahead of a working face and slippage along pre-existing discontinuities in mining are possible candidates for causing rock bursts. To understand such geological phenomena, an experimental method for creating a shear fracture in brittle materials under pure shear loading conditions was developed. Based on the results of the experiments, expressions for estimating shear fracture toughness were derived by using the geometry of the specimen. The test method was used to estimate the shear fracture toughness of sandstone and Sierra White granite.

ARMA 09-142

Experimental and Theoretical Study of Mixed-Mode I+III Crack Propagation and Segmentation

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ABSTRACT: Mixed-mode I+III loading is one of the primary causes of fracture front segmentation. In this work, we developed an experimental technique and theoretical model for studying not only the effect of mode III loading on the onset of fracture segmentation but also the effect of segmentation on the subsequent fracture growth when the KIII/KI ratio was rather small (1%– 10%). The experimental results indicate that a KIII/KI ratio as small as ~ 1% is sufficient for fracture front segmentation even in materials as homogeneous and fracture resistant as polymethyl methacrylate (PMMA).

ARMA 09-096

Some Statistical Aspects of Constant Stress-Rate Testing for Subcritical Crack Growth

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ABSTRACT: In this paper, statistical aspects of the constant stress-rate test were investigated. The effects of the number of specimens on the subcritical crack growth parameters were examined. The grooved disk specimens were used to determine the fracture strength. Seven groups of fictitious data sets with the number of specimens of 5, 7, 10, 20, 40, 80, and 160 at each stress rate were generated by Monte Carlo simulation using the Weibull parameters obtained from the grooved disk tests. Also, the distribution form of the subcritical crack growth parameters and the relation between the parameter A and n was determined.

ARMA 09-063

Observation, Characterization and Modeling of Fracture Initiation in Rock

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ABSTRACT: Observations and characterization of brittle fracture initiation in a micro-heterogeneous material (a consolidated granular sandstone) are conducted using the standard indirect tensile strength test. Acoustic emissions, optical microscopy and scanning electron microscopy (SEM) are employed for monitoring and characterizing the discrete micro-mechanical events preceding macroscopic fracture initiation. The observations suggest that brittle fracture initiation is the end result of a microscopic damage accumulation process. A simple statistical model of damage accumulation in a cohesive granular material is also proposed. The model predicts that heterogeneous rock (in terms of specific fracture energy) will fail macroscopically at lower ultimate stress, but sustain a larger damage concentration, compared to homogeneous rock with the same all other properties. The model is quantitatively linked with the experimental data through this heterogeneity, by matching the measured fracture stress coefficient of variation to that of the model.

ARMA 09-084

Effect of Thermal Shock and Rapid Unloading on Mechanical Rock Properties

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ABSTRACT: Laboratory tests have been conducted to investigate the effects of rapid cooling and rapid unloading on rock damage. Thermal shock experiments were conducted consisting of slow heating up to a temperature of 100C followed by rapid cooling with a fan. Samples were examined after one cycle (relevant to deep core drilling) and five cycles (relevant to ventilation in deep underground mines). The rock damage due to thermal shock was analyzed using before and after P and S wave velocity, porosity, and tensile strength tests. To analyze the effects of rapid unloading, cores collected from depths of 1000~2000 meters were reloaded back to their in-situ stress levels while simultaneously measuring P and S wave velocity. The results from the thermal shock tests were very interesting and showed that crack growth occurred in some rock types subjected to thermal shock (Granite, Diabase with ore veins, KVS) while crack healing occurred in other rock types (Diabase without ore veins, Quartzite, Skarn). Within a rock type the results were consistently crack growth or crack healing. In an effort to understand this behavior, the thermal stresses induced in the rock samples during the shock tests were analyzed. Our hypothesis is that overall crack healing is expected when the amount of crack healing in the central parts of the rock sample (due to slow heating and rapid cooling) exceed the crack growth that is occurring near the surface of the samples (due to rapid cooling), and vice versa.

SESSION 19: ROCK MASS CHARACTERIZATION IV: INDEX TESTS AND CORRELATIONS

ARMA 09-191

The Effect of Stylus Hardness and Some Test Parameters on Cerchar Abrasivity Index

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ABSTRACT: The CERCHAR Abrasivity Index (CAI) is increasingly being used as a measure of rock abrasivity in machine mining and drilling applications. CAI is based on the length of wearflat measured on a steel stylus after it has been drawn a fixed distance across the surface of rock. Currently there are at least two specifications for the steel stylus used in the test. This paper presents the results of a study that examined the effect of stylus hardness on CAI over a range of rock types. The study found CAI decreased linearly with steel hardness and significantly that the rate of reduction in CAI was for the most part independent of rock type. Based on these results a model was derived that can be used to determine CAI for a different stylus hardness. The paper also presents the results of changes in various test parameters including load on the stylus, testing distance, duration of a test, multiple testing in a groove and moisture content of the rock sample.

ARMA 09-130

Shear Strength and Damage Zones of Bedding Planes in Martinsburg Shale

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ABSTRACT: A series of direct shear tests was carried out on bedding planes in specimens of Martinsburg Shale. After the tests were completed, the area of each specimen that was in direct contact with its mate during shear was determined using image analysis software. Damage (contact) areas ranged from about 2% up to 45% of the nominal contact area. Peak and residual friction coefficients were determined for three visually identified categories of bedding planes: fossiliferous, non-coated and mineralcoated, of which the fossiliferous bedding planes had the highest shear strength and mineral-coated the lowest. Variability of the friction coefficient, for each category, was reduced with increasing damage (contact) area. With damage areas exceeding about 20%, friction coefficients could be predicted within about plus/minus 25%, based solely on the visually determined bedding plane characteristics.

ARMA 09-094

Geotechnical Characterization of Sevier and Rome Shale, East Tennessee

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ABSTRACT: A complex mosaic of Sevier (Ordovician) and Rome (Cambrian) Shale are widely distributed throughout the sedimentary sequences in the southern Appalachians. These shales exhibit variable geotechnical characteristics including the strength and durability. We have investigated the factors controlling the Unconfined Compressive Strength (UCS) and Slake Durability Index (SDI) of Sevier and Rome Shale in order to better understand site-specific engineering problems associated

with these shales and to predict their geotechnical behavior. The results have shown the variation in mineral content including expanding clay, calcite, gypsum, and presence of microfractures filled with calcite have significantly affected the durability and strength of shale rock mass. In order to obtain realistic estimate of time-dependent weathering patterns in the Sevier and Rome Shale, we have performed multi-cycle SDI; results have indicates that a 5-cycle SDI better estimates the disintegration pattern of shale and can be used to classify shale in terms of the degree of weathering.

ARMA 09-105

Relationships Between Index and Physical Properties of Weathered Ocala Limestone

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ABSTRACT: The near surface limestones in Florida have been undergoing cycles of deposition and weathering since their formation. These processes coupled with active karstification have resulted in limestone sequences that are highly variable with respect to weathering state and thus engineering and physical properties. Core specimens of Ocala limestone with varying weathering states were tested to determine relationships between physical and index properties. Each weathering state was associated with either two or three hardness values and as weathering state increased hardness decreased. Results show there is no relationship between unit weight and weathering state but the standard deviation of the unit weight values increases as weathering state increases. In general L-type Schmidt hammer, indirect tension, and point load results increase with increasing unit weight. For weathering states of W4 and above, the Schmidt hammer test becomes a destructive test. For weathering states of W3 and above, point load testing may not be appropriate as indicated by very low Is50 values across a wide range of unit weights.

ARMA 09-006

Quality Control of Turkish Calcareous Natural Stone Using the Merkont System

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ABSTRACT: A new statistical derivation system named MERKONT (Marble Control) was developed in this study for the quality control of calcareous natural stone types used as industrial marble. A new classification was made via MERKONT system by taking into consideration the porosity values of 45 different natural stones collected from different parts of Turkey. In the scope of this system, Analysis of Variance: Nested Sampling (Optional) method was used as the statistical system. Natural stones were classified into five different groups on the basis of porosity change. These natural stones were subjected to mineralogical-petrographical analyses with the aim of examining the relationship between this classification, porosity types and checking the accuracy of porosity change limit values. In these analyses, porosity value of the very small crystalline marbles was found to be low and of the porous travertines to be considerably high. In addition, variance range and standard deviation values of each group were reflected in the quality control curve. It was concluded that variance range increased, in turn, quality decreased in parallel with the increase in porosity values of the natural stones.

ARMA 09-016

A New Forecast Method of Opening Displacement and its Engineering Application

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ABSTRACT: With the development of western region in China, the underground openings are built in high depth and high in-situ stress brittle rock-mass. Under these special geological conditions, opening displacement is observed during the definite range around the carven sidewall. Based on the energy dissipation and crack extending, the forecasting method of opening displacement which considers the non- continuous displacement of rock is put forward. In the end, the method is applied in the practice engineering. The forecasting result is accordant with the monitoring data preferably.

SESSION 20: INDUCED FRACTURING – EXOTIC MODES – OUT OF THE ORDINARY

ARMA 09-037

The Distinct Element Analysis for Hydraulic Fracturing Considering the Fluid Viscosity

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ABSTRACT: The flow-coupled DEM simulations are performed to better understand the hydraulic fracturing mechanism and the influence of fluid viscosity. The simulation results were in good agreement with the actual experimental results which containing the AE measurement data. As the results, the followings were found. When the low viscous fluid is used, the fluid is infiltrated into the fracture instantaneously. On the other hand, when the highly viscous fluid is used, the fluid is infiltrated slowly into the crack after the fracture elongates first. Although the tensile cracks are dominantly generated in the simulation, the energy released from a tensile crack becomes small because the tensile strength of rock is obviously small compared with the compressive strength. Such a small AE is easily buried in a noise and hard to be measured in an experiment. Therefore, in AE measurement experiment, shear type AE with large energy is dominantly observed, as many previous researches have indicated.

ARMA 09-129

Poroelastic Analysis of Hydraulic Fracture Propagation

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ABSTRACT: In this paper, the propagation of a fracture in a homogeneous poroelastic rock is studied. A two-dimensional displacement discontinuity boundary element method is developed and employed to model the fracture and to calculate the stress field around the crack. A partially coupled poroelastic model, which couples fluid pressure inside the fracture and rock matrix deformation, is used. The effect of matrix pore-pressure increase and the resulting poroelastic stress on rock deformation and therefore on fracture aperture and fracture propagation is considered. Crack propagation mode and direction is modeled using the unified structural criterion. Numerical results are shown for the fracture propagation trajectories for single and multiple cracks. A parametric study is carried out for different crack propagation speeds, far field stresses, rock cohesion and internal fluid pressures to investigate the influential factors on fracture propagation in a poroelastic rock and the results are compared with those given by an elastic model. We find that matrix pore-pressure increase can change the crack propagation mode and direction.

ARMA 09-119

Multi-Fracture Complexities in Drilling Waste Injection: Wagon-Wheel Uniform Disposal Domain or Secondary Fracture Branching

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ABSTRACT: This paper presents a mathematical study of stress changes in principal horizontal and vertical stresses around the fracture due to an existing fracture using the Sneddon and Illiott model. The study shows that significant stress changes only occur in a localized near-fracture region, and far-field stresses have been minor influenced. Wellbore pressures to initiate a fracture at different potential locations and orientations are analyzed, too. The analysis shows the potential location of fracture opening/propagation is reopening of or branching from the old fracture away from wellbore. Wagon-wheel multi-fracture disposal domain is mathematically confirmed as impractical by computational investigation on stresses increase or fracture width around the wellbore for two types of assumed wagon-wheel (uniform strain and uniform width) multi-fractures. Creation of wagon-wheel multi-fractures would either require an impractical wellbore pressure to overcome the extreme stress due to existing fractures or the fracture width would vanish at the wellbore. This paper also reanalyzes the data from large-scale Mounds experiments of a series of cuttings reinjection and identifies that vertical fracture growth and branching from old fractures away from the wellbore occur more possibly according to the most microseismic events and tiltmeter patterns. This also confirms the above theoretical analysis and conclusions.

ARMA 09-012

Fracture-Conductivity Loss Caused by Geochemical Interactions Between Man-Made Proppants and Formations

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ABSTRACT: The selection of proppant to provide highly conductive pathways in hydraulically-generated fractures is typically based on the proppant crush strength, permeability, availability, and cost. Extensive laboratory data determined conductivity values, obtained using API standardized methods at a variety of simulated well conditions, are available for most proppants. However, post-fracture stimulation well testing indicates that these values are often one to two orders of magnitude too high. In many fields, the productivity of fractures declines rapidly, requiring frequent re-stimulation treatments to remain economically viable. Proppant crushing and embedment, fracturing-fluid damage, and fines invasion are proppant-pack permeability damage mechanisms that have been used to explain this loss of productivity. This paper reports on recent studies that have determined that alumina-based proppant materials may promote geochemical reactions that can occur at a surprisingly rapid rate, even at moderate temperatures, resulting in the loss of porosity and permeability and the creation of fines in the proppant pack. The compatibilities of several man-made proppants ranging from lightweight ceramics to high-strength bauxites with a variety of formations are presented.

ARMA 09-104

An Evaluation of the Effects of Fracture Diagenesis on Fracture Treatments: Modeled Response

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ABSTRACT: Observed reductions in the permeability of propped hydraulic fractures are examined by considering the role of mechanical stresses and the chemistry of pore fluids at elevated temperatures as agents of proppant diagenesis. Stress-enhanced dissolution of proppant increases the density of grain packing and reprecipitation of mineral matter further occludes pores – together these mechanisms additively reduce porosity and permeability. Experiments and analyses are presented which explore the evolution of porosity and permeability in proppant packs subjected to reservoir conditions. Experiments are completed in two modes: in flow-through reactors absent intergranular stresses to evaluate rates of dissolution and reprecipitation on proppant surfaces; and in uniaxially stressed reactors with stagnant fluids to evaluate the relative role of stress in mediating dissolution and porosity reduction. Lumped parameter models are used to evaluate rates of dissolution and chemical compaction in a range of proppants. Mechanisms include mineral dissolution, transport, and re-precipitation of the resulting products in the particle interstices, resulting in a loss of intergranular porosity. The model uses thermodynamic data recovered from the reactor experiments to constrain the projected loss of permeability for the mineralogical composition of available proppants.

ARMA 09-100

Tilt Monitoring of Hydraulic Fracture Preconditioning Treatments

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ABSTRACT: Preconditioning the rock mass by hydraulic fracturing has been carried out at the Northparkes E48 orebody, New South Wales, Australia in 2007-2008. An array of surface tiltmeters was used to monitor and evaluate the hydraulic fractures. Mapping the created hydraulic fractures provided an important quality control feed back on the preconditioning treatment efficiency. This paper presents the mapped fracture volume, dip and dip direction for the first fracture at the start of each treatment shift in borehole D111, and the comparison of fitted and tested surface tilt fields, demonstrating the successful application of surface tiltmeter diagnostic technique as applied to monitoring the hydraulic fracture preconditioning treatments. The results obtained provide a treatment efficiency of about 40% to 60% at the end of most treatments. Most fractures were found to be subhorizontal and tend to dip to the east and north.

SESSION 21: RESERVOIR GEOMECHANICS – FROM BITUMEN TO GRANITE

ARMA 09-010

A $100MM "Rock": Bitumen in the Deepwater Gulf of Mexico

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ABSTRACT: Bitumen encounters in the deepwater Gulf of Mexico are not unusual. In many cases, bitumen presence delayed or prevented reaching programmed TD, adversely affected rig schedule and development planning. The cost from these events

could be as high as $100MM. Based on a series of lab tests that investigate the effect of temperature, pressure, and drilling fluids on bitumen mechanical behaviors, this paper attempts to address four questions: 1) what is bitumen and what are its properties, esp. at in-situ conditions (18000psi stress and 185°F temperature)? 2) where is it found, in pore space or fracture? 3) what are the shapes of the in-situ accumulation? 4) what drives it into the borehole? It has found that the bitumen encountered at various depths may be significantly different. The bitumen adjacent to salt formation is likely stable and could accumulate in a large horizontal spread. The bitumen at the deeper depth has to be close to vertical to survive in-situ stresses. For the horizontal bitumen spread, there is a potential to successfully drill through with a liner, manipulating mud weight may help. However for the vertical column bitumen, increasing mud weight may not be efficient, and sidetracking to avoid further encounter may be more practical. These findings are consistent with the drilling experience in the field, and may help to develop a strategy to manage future bitumen encounters in deepwater Gulf of Mexico.

ARMA 09-120

A Fully-Coupled Finite Element Code for Modeling Thermo-Hydro-Mechanical Processes in Porous Geological Media

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ABSTRACT: This paper describes a new FEM code for modeling coupled thermo-hydro-mechanical processes in porous geological media. For three-dimensional problems, six governing equations, which are based on the conservation equations of momentum, mass, and energy, are presented to describe the coupled THM processes. The three displacement components, the temperature, the pore fluid pressure and the porosity are chosen as the six primary variables. The governing continuum equations are discretized in space by using the Galerkin finite element formulation, and are discretized in time by one-dimensional finite difference scheme. This leads to a large non-symmetric matrix equation that has many small entries along its diagonal, and is therefore ill-conditioned. For efficient equation solution, some special numerical techniques are used in the code in order to deal with the problem of a large non-symmetric ill-conditioned matrix equation. The code was validated against several classical analytical solutions to problems in poroelasticity and thermoelasticity, and tested against a benchmark laboratory experiment that was performed in the Polytechnic University of Catalonia (UPC), Spain.

ARMA 09-089

Aspects of Coupling Between Petroleum Reservoir Flow and Geomechanics

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ABSTRACT: Several aspects of coupling between reservoir fluid flow and geomechanics deformation are examined, namely accuracy, adaptability and running speed. Four different widely used time-coupling techniques (full, iterative, explicit and pseudo) are reviewed and evaluated based on these three aspects. This paper focuses on the iterative time-coupling approach with detailed discussions on how reservoir porosity and absolute permeability are changed with geomechanics. In addition, dual-grid coupling techniques are evaluated with respect to memory storage and CPU requirements for a large field problem. A SAGD example compares fluid-flow and geomechanics results obtained from pseudo coupling versus iterative coupling approaches. A waterflood example shows how iterative time-based coupling method is combined with the dual-grid coupling method to improve CPU speed. In a compaction example where modelling of country rock is crucial, the dual-grid coupling method avoids non-conforming grids when local grid refinement is used around a producing well.

ARMA 09-049

Surface Deformation-based Reservoir Monitoring in Inhomogeneous Media

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ABSTRACT: A semi-analytical model is presented in this paper to predict the surface deformation given the reservoir pressure or volume changes in an inhomogeneous media. The difference in mechanical properties between the reservoir and overburden or overburden "layering" is accounted for using the moduli perturbation method. Essentially a center of dilatation point source solution in an inhomogeneous half-space is adopted and replaces the existing center of dilatation Green's function in homogeneous half-space. With the moduli perturbation method, the effect of the modulus contrast on deformation is transformed into integration over the interface between different mechanical properties, which makes it sufficiently versatile to implement for different field geometries other than horizontal layers. As a case demonstration, the proposed method is used to calculate the vertical displacement for a sample problem in the literature and compare with the result from a geomechanically coupled reservoir simulator. The semi-analytical model presented in this paper can be used as a forward model that accounts for the effects of inhomogeneous mechanical properties in any inversion program to obtain more accurate volume and pressure changes in reservoir. It can be used as a calibration tool to more accurately history-match reservoir parameters from the measured surface deformation.

ARMA 09-013

Evolution of Fracture Permeability in Granite and Its Evaluation via Coupled Chemo-Mechano Conceptual Model

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ABSTRACT: A coupled chemo-mechano conceptual model is presented to follow the evolution of fracture permeability observed in flow-through experiments in a single rock fracture in granite. The experiments are conducted under constant confining pressures of 5 and 10 MPa with differential water pressures ranging 0.01-0.5 MPa, and temperatures of 20 and 90 °C. Permeability measured shows a monotonic decrease with time, via apparent steady state after relatively short periods at 20 °C. A presented model addresses the two dissolution processes at contacting asperities and free walls within fractures, and also describes the multimineral dissolution behavior, showing a capability that the evolution of fracture aperture (or related permeability) may be followed with time under an arbitrary temperature and pressure conditions. Predictions utilizing the model proposed in this study show a relatively good agreement with the experimental measurements, although an abrupt reduction observed is incapable of being replicated, that is due to an unaccounted effect in the current model.

SESSION 22: LIDAR AND REMOTE SENSING FOR ROCK MASS CHARACTERIZATION II

ARMA 09-125

The Measurement and Monitoring of Coal Mine Subsidence Using Interferometric Aperture Radar

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ABSTRACT: A methodology has been developed and verified for producing differential interferograms capable of identifying and measuring subsidence above coal mines in Utah. Time-lapsed images acquired over a period of 92 days were used to locate areas of ground movement and to image centimeter-scale displacements associated with mining induced subsidence. 28 cm of subsidence was measured using ALOS images acquired two months prior and one month after a larges-scale barrier pillar collapse at the Crandall Canyon mine. This measurement corresponds with field measurements of 30 cm recorded at GPS monitoring locations. A second mine was studied using ALOS scenes and active zones of subsidence were identified above an area of current longwall mining. A peak subsidence rate of 0.15 cm/day was measured above one of the panels using differential InSAR and this is consistent with field measurements of 0.14 cm/day. This preliminary work indicates that interferometric synthetic aperture radar can be used to measure and monitor coal mining induced subsidence in a comprehensive, timely, and cost-efficient manner.

ARMA 09-082

Estimating the Extent of the Disturbed Rock Zone around a WIPP Disposal Room

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ABSTRACT: The disturbed rock zone (DRZ) is an important feature which is evaluated in the Waste Isolation Pilot Plant (WIPP) performance assessment (PA) to predict post-closure repository performance. Mining of a WIPP disposal room disturbs the stress state sufficiently to cause fracturing of the surrounding rock, and this fracturing will alter the mechanical and hydrological properties of the salt. DRZ extent, and permeability, controls the majority of the brine that enters or exits the repository in PA modeling of the undisturbed scenario. Extensive laboratory data from experiments performed on rock salt demonstrate that damage can be modeled in terms of stress invariants. In this paper the DRZ extent is calculated based on a dilatant damage criterion. The calibrated damage factor C in the damage criterion is determined by comparing ultrasonic wave velocity field measurements obtained in the S-90 drift with a numerical analysis that predicts the salt's behavior. Ultrasonic velocities decrease in the presence of microcracks and loosened grain boundaries associated with salt damage. The most extensive DRZ exists during early times, within the first ten years of mining. The maximum predicted DRZ surrounding a WIPP disposal room is approximately 2.25 m below, 4.75 m above, and 2 m laterally. This paper also presents several lines of evidence, based on previous studies, that support the prediction of DRZ size by applying a WIPP specific damage criterion calibrated using ultrasonic velocity measurements.

ARMA 09-143

Attenuation Analysis of Rayleigh Waves used to Locate Shallow Manmade Tunnels

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ABSTRACT: The Attenuation Analysis of Rayleigh Waves (AARW) algorithm was applied to multi-channel surface wave seismic data acquired at two test sites for the purpose of locating manmade tunnels in the Earth's shallow subsurface. The surface wave data were acquired by incrementally moving a 24-channel geophone array and source along a traverse oriented perpendicular to the center-line of the tunnel. The near source-receiver offsets were 3 & 6 m, respectively; the 4.5 Hz geophones were spaced at 0.5 m. The geophone array geometry was optimized for nominal tunnel depths and diameters of ~1 m. Using AARW, the authors were able to reliably determine tunnel locations and delineate void geometries. Confidence levels and uncertainties with respect to void locations and geometries are discussed herein. Electrical resistivity or GPR data were acquired along each traverse for comparison purposes. This study demonstrates that the AARW algorithm may enable engineers to detect tunnels and estimate the geometry of the same.

ARMA 09-141

Non-Contact Detection of Acoustic Emission Signals from Rock Surfaces

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ABSTRACT: The purpose of the research was to investigate the feasibility of developing advanced acoustic emission (AE) monitoring for rock structure stability assessment. The equipment involves a laser interferometer based non-contact detection system to perform monitoring of AE activity in the process of rock deterioration. Two laser based sensing units were tested in this effort, namely, the unit using photo-induced electromotive force (PI-EMF) and the one using two-wave mixing (TWM) technique. In the initial experiments, TWM technique showed superior performance and technical maturity for AE signal detection on rock surface, while the PI-EMF technique needs further development. The TWM sensing unit was also compared with conventional piezoelectric transducer in AE monitoring test on rock specimens. In these laboratory tests, TWM sensing unit showed excellent performance. The frequency band, fidelity and signal-to-noise ratio are competent for the projected use. The significance of these tests is that it demonstrated that the TWM sensing unit could detect AE signals with similar sensitivity and accuracy to that of the conventional piezoelectric transducers. Therefore, the laser-based sensing unit (TWM) can be incorporated for development of AE based rock stability monitoring system. A series of acoustic emission tests were then conducted on specimens of rock, including weathered sandstone, shale and coal. The AE data were used for failure criteria development. The instrumentation for AE data collection has two channels: one is used for the laser-based TWM sensing unit; the other is used for conventional piezoelectric system as reference. Thirteen rock specimens (3 sandstone, 5 shale, and 5 coal) were tested under uniaxial compression for the purpose of collecting AE data for parametric analysis and pattern recognition study. Finally criteria were established for prediction of instability development in the rock specimens.