TABLE OF CONTENTS

SPONSORS

The 44th U.S. Rock Mechanics 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, educators, and students in the fields of rock mechanics and rock engineering.

The following companies have generously provided support for the 44th symposium:

Agapito Associates, Inc. Sponsor of the Monday, June 28th Symposium Lunch

Advantek International, Sponsor of All Morning Coffee Breaks

Chevron, Sponsor of Student Scholarships for Symposium Registration

ConocoPhillips, Sponsor of the Tuesday, June 29th Symposium Lunch and Refreshments for the Poster Sessions

Energy & Geoscience Institute, General Symposium Support

Golder Associates, Inc., Sponsor of the Wednesday, June 30th Afternoon Ice Cream and Coffee Break

MTS Systems Corp., Sponsor of the Sunday, June 27th Opening Lecture and Reception

Schlumberger

TerraTek

EXHIBITORS

BOOTH # 1

AEG: Association of Engineering and Environmental Geologists

PO Box 460518

Denver, CO 80246

www.aegweb.org

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 # 4

Weatherford Laboratories

8845 Fallbrook Drive

Houston, TX 77064

www.weatherfordlabs.com

Weatherford Laboratories rock mechanics laboratory provides core-based testing and engineering analysis services to optimize reservoir and enhance production. Weatherford Laboratories offer many different kinds of testing services with applications to hydraulic fracture design, wellbore stability, sand production, and other reservoir engineering and geophysical applications for conventional and unconventional reservoirs.

BOOTH # 5

Applied Geodynamics, Inc.

P.O. Box 772129

Steamboat Springs, CO 80477

www.capprex.com

The Controlled Foam Injection (CFI) method uses high-pressure foam to initiate and propagate controlled fracturing in rock (or concrete). An injection barrel, incorporating a special hole-bottom seal, is used to inject foam into the bottom of pre-drilled holes in the rock. The high viscosity of the foam combined with the energy stored in the gas phase result in very controlled and efficient breakage. Airblast and flyrock are reduced to very benign levels.

BOOTH # 6

Golder Associates, Inc.

18300 NE Union Hill Road

Redmond, WA 98052

www.golder.com

Golder Associates is a leading international geo-engineering consulting firm, offering geomechanics, hydrodynamics, geologic, and geophysical services 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 # 7

MTS Systems Corp.

14000 Technology Drive

Eden Prairie, MN 55344

www.mts.com

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 # 8

The University of Texas at Austin

Department of Civil Engineering

1 University Station C1792

Austin, TX 78712-0280

www.caee.utexas.edu/prof/tonon

Rock mechanics and tunneling at the University of Texas, Austin. Research: DEM, rockfall impact fragmentation; rock block stability analysis under general loading for underground excavations, slopes, scour, prediction of groundwater inflow; structural synthetic fibers for shotcrete and final lining; risk analysis with imprecise probabilities; face stability in mechanized tunneling. Education: online certificate in tunneling.

BOOTH #9

Geokon, Inc.

48 Spencer Street

Lebanon, NH 03766

www.geokon.com

Geokon, Inc. manufactures a full range of high-quality geotechnical instrumentation suitable for monitoring the safety and stability of civil and mining structures. Geokon's Vibrating Wire sensors exhibit excellent long-term stability, accuracy, and reliability even in the most adverse conditions.

BOOTH # 10

TerraTek/RPSEA

1935 S. Fremont Dr.

Salt Lake City, UT 84104

www.rpsea.org

Sustaining Fracture Area and Conductivity of Gas Shale Reservoirs for Enhancing Long-Term Production and Recovery--This theoretical and experimental project is aimed at understanding the multiple causes of loss of hydraulic fracture area and conductivity in gas shale reservoirs. The objective is to define solutions to prevent the resulting loss of production. This multi-disciplinary project tasks include an evaluation of reservoir geology, mechanical properties, in-situ stress, and rock-fluid interactions.

BOOTH # 11

MetaRock Laboratories, Inc.

6723F Stella Link Road

Houston, TX 70005

www.metarocklab.com

MetaRock Laboratories, Inc. is a unique and diversely skilled Geo-Mechanics laboratory. We are able to provide high quality testing services (i.e., Triaxial, Uniaxial, UCS, SCAL, etc) on rock samples. We have extensive experience in designing and developing testing apparatus/vessels and pumps. More recently, we have developed a highly exceptional capability in the acoustics testing realm that is gaining much attention and notoriety.

BOOTH #12

MALA GeoScience USA, Inc.

2040 Savage Road

PO Box 80430

Charleston, SC 29416

www.malags.com

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 # 13

ADAM Technology

Suite 3

41 Belmont Avenue

Belmont, WA, 6104

Australia

www.adamtech.com.au

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 #14

Ruen Drilling, Inc.

PO Box 267

2320 River Road

Clark Ford, ID 83811

www.ruendrilling.com

Ruen Drilling, Inc., established in 1974, provides drilling services throughout the United States and Peru, South America. Services include core drilling for geotechnical, mineral exploration, and geothermal industries. Hole depth capacities include horizontal coring to 2500 ft. as well as vertical coring to over 10,000 ft. Ruen Drilling utilizes track, skid, truck and helicopter supported drills. The quality sampling, which the company provides, allows clients and project owners to generate defensible quality pre-design reporting. Ruen Drilling strives to train its crews in this manner and supports them with the equipment needed to generate the sample quality, along with providing the services in a safe, timely fashion and within budget parameters.

BOOTH #15

GCTS Testing Systems
6103 S. Maple Avenue, #1
Tempe, AZ 85283
www.gcts.com

GCTS provides a full line of computer servo-controlled testing systems for rocks, soils, pavements, and construction materials, advanced systems for Triaxial, Direct Shear, Point Load, Indirect Tension, Hydraulic Fracture, Poly-Axial, Hollow Cylinder, Ultrasonic, and other specialized equipment including high-pressure/high-temperature triaxial cells.

BOOTH #16

Rocscience Inc.
31 Balsam Avenue
Toronto, Ontario M4E 3B5
Canada
www.rocscience.com

Rocscience Inc., formed in 1996 in Toronto, Canada, has over 6,000 customers in over 100 countries. As a spin-off company from the University of Toronto, we have continued the evolution of ideas and technology over the years, creating new software products in the field of geomechanics while maintaining a close connection to the research environment. Our company offers 11 Windows programs, specializing in 2D and 3D analysis and design programs for civil engineering and mining applications. Our high-quality software allows engineers to quickly and accurately analyze surface and underground structures in rock and soil, thereby improving safety and reducing the cost of design projects.

BOOTH #17

Engineering Seismology Group
20 Hyperion Court
Kingston, Ontario K7K 7G3
Canada
www.esg.ca

ESG is a world leader in industrial microseismic monitoring. We design, manufacture and install systems for mining, petroleum and geotechnical applications where information is required for operational decisions. In mining, ESG is the top provider of commercial products and services for the monitoring of mine seismicity with applications in ground support design, evaluation of alternative mining methods, reducing seismic hazard, and ensuring the safety of personnel.

ACKNOWLEDGEMENTS

Organizing Committee

SIDNEY GREEN
Symposium Executive Committee
Chair, Finance/Sponsorship Committee
Schlumberger and University of Utah

JOHN McLENNAN
Symposium Executive Committee
Chair, Technical Program Committee
University of Utah

PETER SMEALLIE
Symposium Executive Committee
American Rock Mechanics Association

ANTONIO BOBET
Purdue University

JOSEPH CARVALHO
Golder Associates

ALVIN CHAN
Shell International

BILL DERSHOWITZ
Golder Associates

JAMES DONOVAN
University of Utah

DEREK ELSWORTH
Chair, Publicity-Promotion Committee
Penn State University

BILL GATES
Kleinfelder, Inc.

GEN GREEN
The Nature Conservancy

QUAN GUO
M-I SWACO

GANG HAN
Hess Corporation

FRANK HANSEN
Sandia National Laboratories

MICHAEL HARDY
Agapito Associates

SHERRI HEROUX
TerraTek, A Schlumberger company

CLIFF HOLLE
Chair, Field Trips/Technical Tours
Energy & Geoscience Institute, University of Utah

TERI NICHOLS
ConocoPhillips

GANGERICO RAMOS
ConocoPhillips

ANN SPENCER

CEZAR TRIFU
ESG

AZRA TUTUNCU
Geomechanics Engineering & Research

ERIK WESTMAN
Virginia Tech

SARAH WILSON
Jacobs Associates

DAVID P. YALE
ExxonMobil Upstream Research Company

ARMA Board of Directors

AZRA NUR TUTUNCU, PRESIDENT
Geomechanics Engineering & Research

MARK ZOBACK, VICE PRESIDENT
Stanford University

WILLIAM DERSHOWITZ, TREASURER
Golder Associates

GANGERICO RAMOS, SECRETARY
ConocoPhillips

SARAH H. WILSON, IMMEDIATE PAST PRESIDENT
Jacobs Associates

AHMED ABOU-SAYED
Advantek International

DON BANKS
Vicksburg, Mississippi

ANTONIO BOBET
Purdue University

JAMI GIRARD DWYER
Barrick Goldstrike

SIDNEY J. GREEN
Schlumberger and University of Utah

ANTHONY IANNACCHIONE
University of Pittsburgh

MARY MacLAUGHLIN
Montana Tech

DAVID P. YALE
ExxonMobil Upstream Research Company

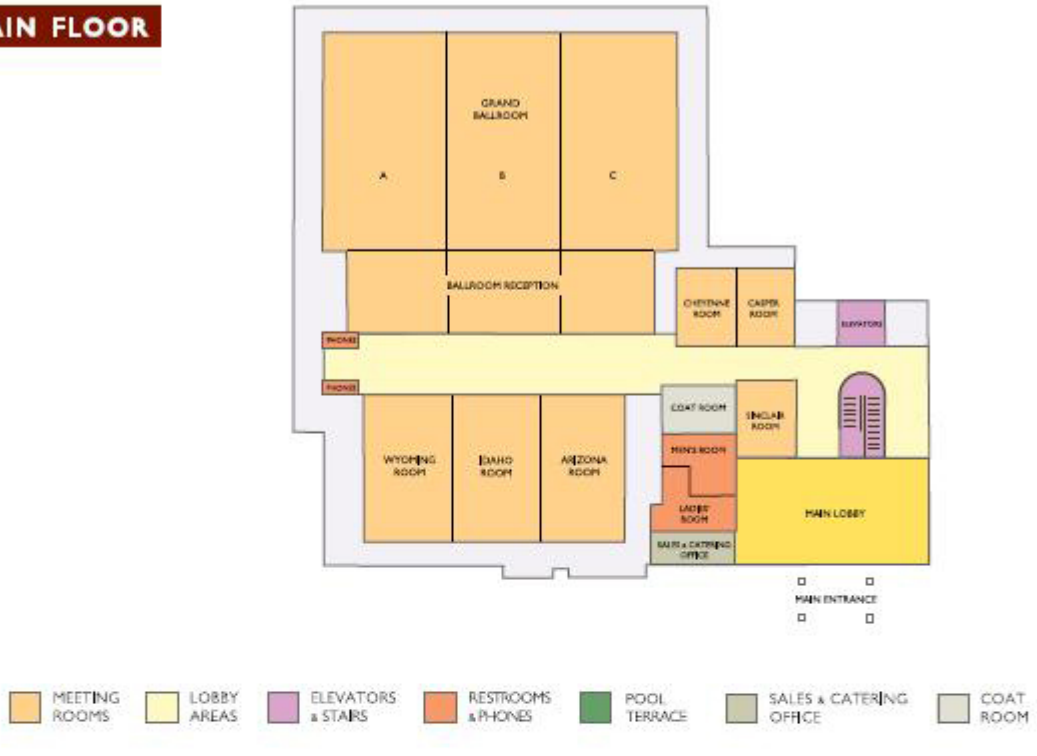
HOTEL MEETING ROOMS

For more information, please visit the Little America's Website: www.littleamerica.com/slc/index.html

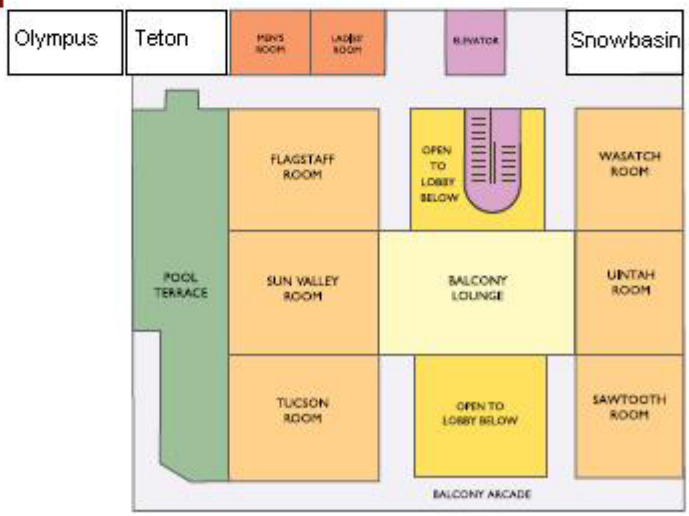
MEETING PLANNER GUIDE · SALT LAKE CITY

LITTLE AMERICA Hotel

MAIN FLOOR



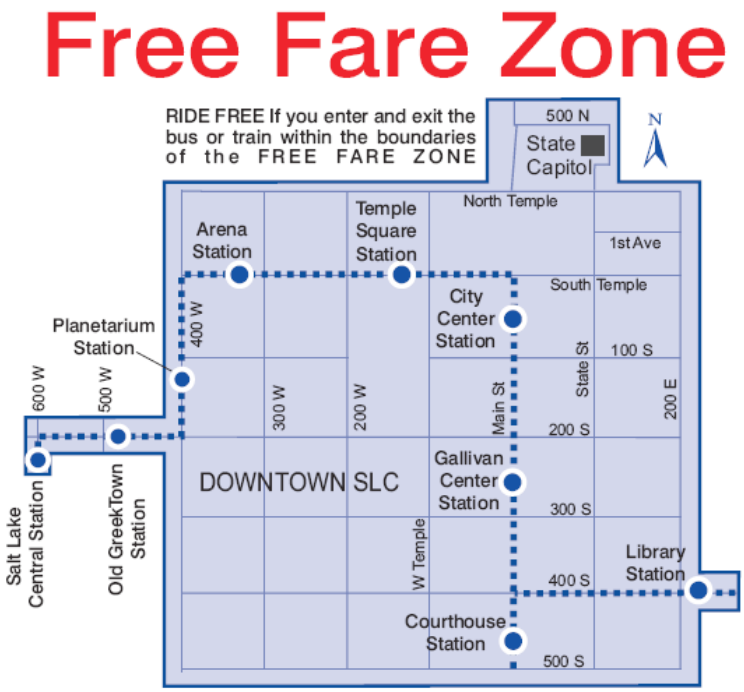
SECOND FLOOR



GENERAL INFORMATION

Hotel/Maps/Transportation/Parking

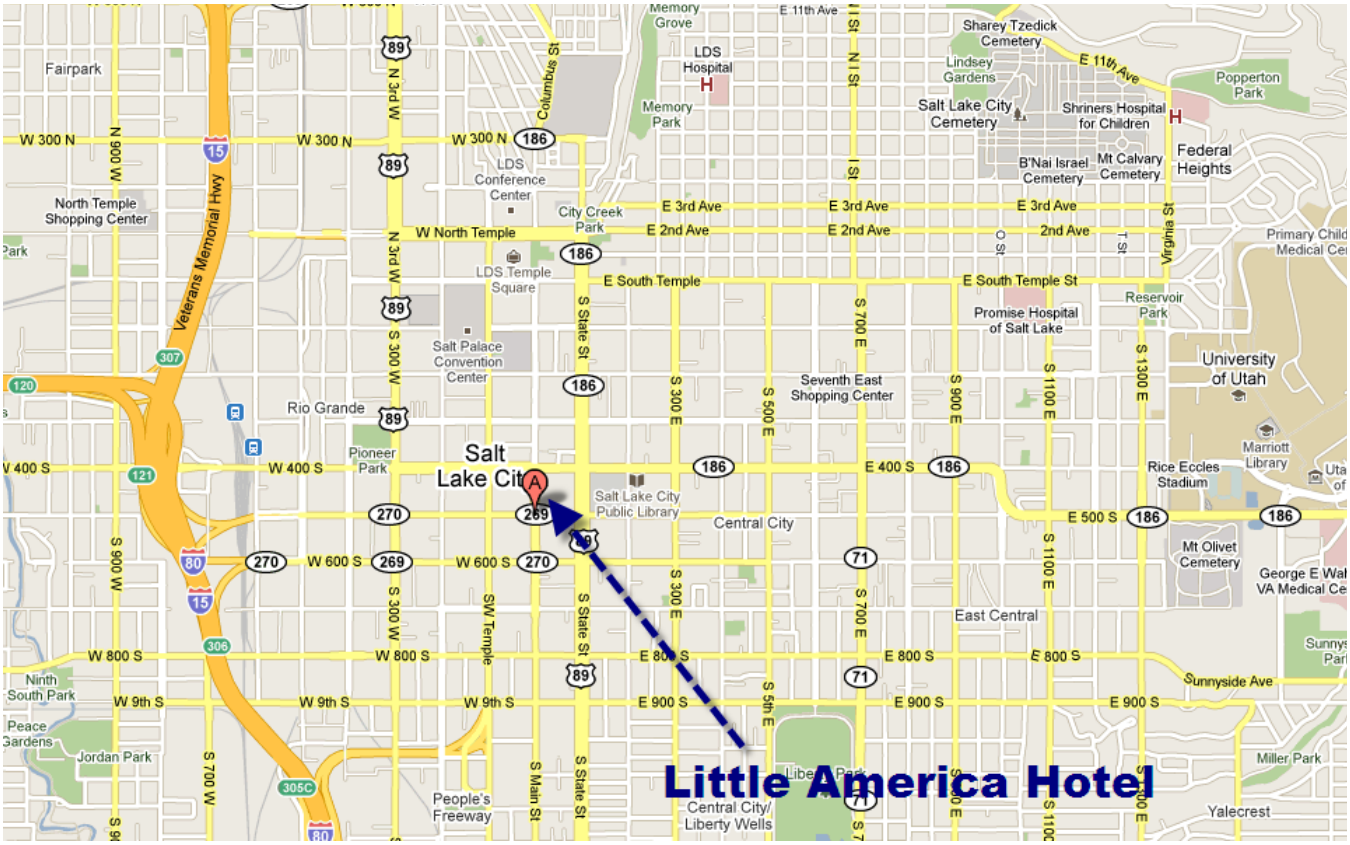
The Little America Hotel, 500 South Main Street in Salt Lake City is located in the pedestrian-oriented business, cultural, and entertainment section of the city. The effective TRAX system, a surface light rail system, runs adjacent to the hotel with a stop located outside a hotel entrance. In the downtown area, TRAX is free. (http://www.rideuta.com/ridingUTA/payingFare/freeFareZone.aspx)



Salt Lake International Airport is a fifteen-minute taxi ride from the Little America Hotel, and a one-way fare is approximately $20.

Parking is free at the hotel.

Downtown restaurant information is available from the concierge or at http://www.dininginutah.com/downtownrestaurants.htm


Little America Hotel
Salt Lake City
Fairpark
Memory Grove
LDS Hospital
Sharey Tzedick Cemetery
Lindsey Gardens
Popperton Park
Salt Lake City Cemetery
Shriners Hospital for Children
Federal Heights
B'Nai Israel Cemetery
Mt Calvary Cemetery
North Temple Shopping Center
LDS Conference Center
City Creek Park
LDS Temple Square
Salt Palace Convention Center
Promise Hospital of Salt Lake
Reservoir Park
University of Utah
Seventh East Shopping Center
Rio Grande
Pioneer Park
Salt Lake City Public Library
Central City
Rice Eccles Stadium
Marriott Library
Mt Olivet Cemetery
East Central
Ninth South Park
Peace Gardens
Jordan Park
Sunnyside Ave
Miller Park
People's Freeway
Central City/ Liberty Wells
Yalecrest
Veterans Memorial Hwy
W 300 N
E 11th Ave
E 3rd Ave
E 2nd Ave
W North Temple
E South Temple
E South Temple St
W 400 S
E 400 S
E 500 S
W 600 S
W 800 S
E 800 S
W 9th S
E 900 S
N 3rd W
S 300 W
S State St
S 300 E
S 500 E
S 700 E
S 900 E
S 1100 E
S 1300 E
SW Temple
S Main St
S 5th E
Columbus St
I St
Virginia St

REGISTRATION

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

Saturday, June 26th	7:00 a.m. – 8:30 a.m.
Sunday, June27th	7:00 a.m. – 9:00 p.m.
Monday, June 28th	7:00 a.m. – 5:30 p.m.
Tuesday, June29th	7:00 a.m. – 5:30 p.m.
Wednesday, June30th	7:00 a.m. – 1:15 p.m.

EXHIBIT HALL HOURS

Sunday, June 27th	7:00 p.m. – 9:00 p.m.
Monday, June 28th	10:15 a.m. – 4:00 p.m.
Tuesday, June 29th	10:15 a.m. – 4:00 p.m.
Wednesday, June 30th	8:00 a.m. – 10:45 a.m.

BREAKFAST FOR PODIUM PRESENTERS

All speakers and session chairs are required to attend the speaker's breakfast from 7:15 a.m. – 8:20 a.m. in the Arizona Room 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 FOR PODIUM PRESENTATIONS

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

Monday, June 28th	7:00 a.m. – 5:30 p.m.
Tuesday, June 29th	7:00 a.m. – 5:30 p.m.
Wednesday, June 30th	7:00 a.m. – 3:15 p.m.

PROGRAM

SATURDAY, JUNE 26TH

Registration, Main Floor-Coat Room	7:00 a.m. - 8:30 a.m.
Workshop on Geomechanics, Treasure Mountain Inn, Park City	8:30 a.m. - 8:00 p.m.
Buses Leave 8:30 a.m. from Little America Hotel Lobby	

SUNDAY, JUNE 27TH

Registration, Main Floor-Coat Room	7:00 a.m. - 9:00 p.m.
ARMA Board of Directors Meeting, Uintah Room	8:00 a.m. - 4:00 p.m.
Field Trip: Kennecott Mine and TerraTek Laboratory	9:00 a.m. - 4:00 p.m.
Buses Leave at 8:30 a.m. from Little America Hotel Lobby	
Field Trip: Wasatch Front Tour and TerraTek Laboratory	9:00 a.m. - 4:00 p.m.
Buses Leave at 8:30 a.m. from Little America Hotel Lobby	
Exhibit Set Up, Ballroom Reception Area	2:00 p.m. - 5:00 p.m.
Opening Remarks Grand Ballroom	6:00 p.m. - 7:00 p.m.
Azra Tutuncu, President, ARMA	
Sidney Green, John McLennan, Symposium Chairs	
MTS Invited Lecture	
Introduction: Greg Pence, MTS Systems Corp.	

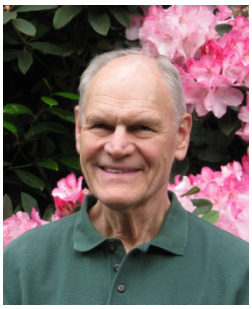
Speaker:

Richard Robbins, "Dealing with Rock Mechanics Challenges in a Machine Bored Tunnel"

SYNOPSIS:

Deep overstressed rock can show us what we might have been able to anticipate. For some of us that work in tunnels, this is a learning experience, and it is sobering. A difficult tunnel is being built through the Andes Mountains of Peru. It will transfer much needed water to the Western slope and generate hydro power. A Brazilian contractor operating a 5.3 m-diameter tunnel borer is struggling to complete this 14 km tunnel. The mountain is fighting back, and after having bored over 10 km of tunnel, it now looks as though the mountain may be winning. This presentation illustrates the story. There may be lessons to be learned from this experience for rock engineers as well as for tunnel builders.

BIOGRAPHY:



Richard Robbins is known for pioneering development of tunnel boring machines and for enhancing the United States' worldwide technological leadership position in rock tunnel construction. Robbins' father, James S. Robbins, developed the first rock tunnel boring machine in 1952 and founded The Robbins Company, which is now a worldwide company with representation in over 25 countries. Richard Robbins has been responsible for leading or creating the company's subsequent innovations from large diameter hard rock disc cutters to the first Double Shield TBM for Italy's Orichella Project in 1972. "One of the most memorable projects I've worked on is the Channel Tunnel. We designed machines that successfully bored through water-bearing ground at 10 bar pressure - a much higher pressure than had ever been done before," said Robbins. The 39 km (24 mi) long Channel Tunnel was completed in 1991 following the use of five Robbins shielded TBMs placing precast concrete segments. Another career highlight was a machine developed for the RER metro system in Paris, France in 1965. "We created the world's first below water, pressure bulkhead shielded machine using air pressure. This maintained the tunnel face under pressure while the rest of the tunnel remained at atmospheric pressure. All future slurry and EPB designs had their genesis in this machine." Richard Robbins continues to work in the tunneling industry as a member of the Board of Directors of The Robbins Company and as a collaborator in development projects. He sees much work to be done in the future. "The next step will be to develop designs for a wide range of geologic conditions and for standardized elements that will shorten projects and reduce capital costs."

Opening Reception/Exhibits Open, Ballroom Reception	7:00 p.m. - 9:00 p.m.

Sponsored by MTS Systems Corp.

MONDAY, JUNE 28TH

Registration, Main Floor-Coat Room	7:00 a.m. - 5:30 p.m.
Speakers' Ready Room, Registration Desk	7:00 a.m. - 5:30 p.m.
Speakers' Breakfast, Arizona Room	7:15 a.m .- 8:20 a.m.

PODIUM PRESENTATIONS AND INVITED LECTURES

Session 1--Rock Characterization I: Fracture Mechanics -Experimental

Ballroom A 8:30 a.m. - 10:15 a.m.

Session Coordinator: Antonio Bobet; Chairs: Herbert Einstein, Matthew Mauldon

Invited Speaker: Roberto Suarez-Rivera,
"Geomechanics for Unconventional Reservoirs" 8:30 a.m. - 8:55 a.m.

SYNOPSIS:

Unconventional reservoirs have been said to be "easy to find but difficult to fracture." This is so because the same formations that constitute the source of hydrocarbons also constitute the reservoir, the bounding units for fluid migration and the containing units for fracture propagation. In addition, for tight gas shales, some of the desirable conditions that enhance reservoir quality (e.g., organic content, degree of maturation, and pore pressure) also enhance the development of the minimum horizontal stress and make these units difficult to fracture. Geomechanics in unconventional reservoirs requires understanding reservoir heterogeneity and the spatial distribution of material properties (at small to large scales). It requires understanding important consequences of elastic anisotropy on in-situ stress development, and on near wellbore stress concentrations (to predict breakdown pressures). It also requires understanding the effect of reservoir texture on fracture propagation and fracture complexity. And finally, it requires understanding all the geologic, petrologic, geochemical, petrophysical, and mineralogical properties that contribute to the observed mechanical properties. Above all, geomechanics of unconventional reservoirs (gas shales and oily shales) is not limited to rock mechanics evaluations, and must include a broader knowledge of the physical, chemical, and geologic process taking place, including their mutual interactions.

BIOGRAPHY:

Roberto Suarez-Rivera is a Scientific Advisor and head of the Schlumberger Innovation Center in Salt Lake City, Utah. He holds a BS in Mechanical engineering from North Carolina State University, and MS, and PhD degrees in Rock Mechanics from the University of California, Berkeley. Dr. Suarez-Rivera has 20 years with Schlumberger, including 7 years of field service engineering with Dowell Schlumberger and 13 years with TerraTek as a scientist and consultant in petroleum-related rock mechanics. Dr. Suarez-Rivera also worked with the Norwegian Institute of Rock Mechanics IKU and the Rock Mechanics Group at the Lawrence Berkeley National Laboratory. He has authored papers on mechanical property evaluations and on analysis of geo-material mechanical behavior and has patents on the application of these concepts to reservoir evaluation, hydraulic fracturing and property characterization. Dr. Suarez-Rivera's current focus of attention is on the impact of heterogeneity and material anisotropy on the evaluation of wellbore stability, well productivity, in-situ stress development, and completion design for unconventional reservoirs.

9:00 An experimental study of crack coalescence in pre-cracked specimens under uniaxial compression, H. Lee, 369

9:15 Crack growth and coalescence mechanism in granite material containing two surface flaws under uniaxial compression, P. Yin, 286

9:30 Influence of 3D Internal Crack Spacing on Strength and Crack Propagation Pattern in Rock Sample Subjected to Tensile Stress, L. Yang, 374

9:45 Deviation from Linear Elastic Fracture in Near-Surface Hydraulic Fracturing Experiments with Rock, R.Y. Makhnenko, 237

10:00 Observation and Modeling of Hydraulic Fracture Initiation in Cohesionless Sand, H. Jasarevic, 360

Session 2--Field Cases, Caverns (Civil)

Ballroom B 8:30 a.m.- 10:15 a.m.

Session Coordinator: Sarah Wilson; Chairs: Brun Hilbert, Bill Gates

Invited Speaker: Matthew Pierce, "Fracture Network Engineering" 8:30 a.m. - 8:55 a.m.

SYNOPSIS:

Fracture Network Engineering is defined as the design, analysis, modeling, and monitoring of in-field activities aimed at enhancing rock mass disturbance. The nature and level of disturbance can vary widely, from shearing of pre-existing fractures (e.g. to enhance permeability) to complete disintegration (e.g. to permit extraction). This discipline relies on novel techniques for modeling jointed rock masses and for correlating microseismic field observations with simulated microseismicity from these models. On the one hand, data acquisition and Enhanced Microseismic Analyses (EMA) are used to map a disturbed or enlarging fracture network in space, magnitude, and evolution. On the other hand, Synthetic Rock Mass (SRM) numerical models are developed to study rock mass behavior at a representative scale (e.g. 10-100m).

BIOGRAPHY:

Mr. Pierce received his BSc. in Geotechnical Engineering and his MSc. in Mining Engineering from Queen's University in Kingston, Canada. He is a registered professional engineer in Canada and his current professional position is Principal Engineer with Itasca Consulting Group in Minneapolis, MN. Mr. Pierce's research/consulting interests include the prediction of caveability, fragmentation, subsidence, draw/recovery and infrastructure stability associated with block, panel and sublevel caving. Recent research has focused on application of DEM to the study of jointed rock mass strength and deformation behavior and the gravity flow of caved rock.

9:00 Rock Mass Analysis and Support Measures for the No Business Creek Tunnel Project, Gwinnett County, Georgia (A Case Study), Ashley Heckman, 401

9:15 Thoughts on Fault Zone Characterization for Tunneling, D.P. Richards, 386

9:30 Design and construction of the lake tap tunnel at Lake Dorothy Hydro, Juneau, Alaska , S.H. Brandon, 346

9:45 Geological and Geomechanical Modeling Procedures Suitable for Civil, Mining and Petroleum Engineering, V.R. Marchesi, 364

10:00 Rock Engineering Assessments for Dam Stability Studies – Examples from New Zealand, S.A.L. Read, 411

Session 3--Petroleum Reservoir Geomechanics I

Ballroom C 8:30 a.m. - 10:15 a.m.

Session Coordinator: Gang Han; Chairs: Marc Hettema, Erling Fjær

Invited Speaker: Pete Rose, "Creation of an Engineered Geothermal System through Hydraulic and Thermal Stimulation" 8:30 a.m. - 8:55 a.m.

SYNOPSIS:

The Coso geothermal field is an excellent setting for testing Enhanced Geothermal System (EGS) concepts. Fluid temperatures exceeding 350oC have been measured at depths less than 10,000 ft. and the reservoir is both highly fractured and tectonically stressed. However, some of the wells within the reservoir are impermeable. High rock temperatures, a high degree of fracturing, high tectonic stresses and low permeability are the qualities that define an ideal candidate-EGS reservoir. The objective of this project was to create an EGS on the margins of the Coso geothermal field through hydraulic, thermal, and/or chemical stimulation.

Key to the creation of an EGS is an understanding of the relationship a.m.ong natural fracture distribution, fluid flow, and the a.m.bient tectonic stresses that exist within a resource. Once these relationships are determined, it is possible to design a hydraulic and thermal stimulation of a candidate injection well as the first step in the creation of a heat exchanger at depth. The success of the experiment can then be quantified through hydraulic, microseismic, geomechanical, and geochemical measurements. From the lessons learned at Coso, it will be possible to design and create an EGS wherever appropriate tectonic, thermal and hydraulic conditions exist, thereby allowing geothermal operators to greatly extend their developmental reach beyond the relatively few known geothermal resources.

BIOGRAPHY:

Peter Rose, with the Energy and Geoscience Institute at the University of Utah, conducts research into the design, creation, and characterization of Engineered Geothermal Systems through a variety of hydraulic, thermal and chemical approaches. He develops novel dissolution agents and fluid diversion agents for the purposes of chemical and hydraulic stimulation. Dr. Rose also researches thermally stable and reactive tracers for use in characterizing reservoir pore volumes, fluid-residence times, and near-wellbore fracture surface areas for use in geothermal, petroleum, and CO2 reservoirs. In addition, he and his group are developing a borehole fluorimeter for measuring fluid-flow rates in geothermal wellbores.

9:00 Observation and Characterization of Hydraulic Fracture in Cohesionless Sand, E. Golovin, 359

9:15 Finite-element analysis of deliberately increasing the wellbore fracture gradient, S. Salehi, 202

9:30 Homogenized models of stress-sensitive tight sand rocks, L. Jeannin, 338

9:45 Effect of Shale Bedding Plane Failure on Wellbore Stability – Example from Analyzing Stuck-Pipe Wells, B. Wu, 350

10:00 Criterion for Fractures Crossing Frictional Interfaces at Non-orthogonal Angles, H. Gu, 198

Tour: Olympic Winter Park, Park City & Factory Outlet Stores 10:00 a.m. - 3:00 p.m.

Meet in lobby; bus leaves 10:00 a.m. from Little America Hotel

Coffee Break/Exhibits Open, Ballroom Reception 10:15 a.m. - 10:45 a.m.

Sponsored by Advantek International

PODIUM PRESENTATIONS

Session 4--Slopes, High Walls, Stabilization

Ballroom A 10:45 a.m. - 12:00 noon

Session Coordinator: James Donovan; Chairs: Mary MacLaughlin, John Read

10:45 Full-scale 3D slope stability analysis of Sarcheshmeh mine west wall, A. Mortazavi, 486

11:00 Toward a Tool for Managing Uncertainty in Large Open Pit Modelling– Finite Element Analysis of Jointed Rock Masses, R.E. Hammah, 334

11:15 Simulation of rock slope failures with the numerical manifold method, Y.J. Ning, 311

11:30 3d Hydro-mechanical simulation of faulted open pit slopes, D.A. Beck, 425

11:45 A Three-Dimensional Model for Rock Slopes Based on Micromechanics, L.J. Lorig, 163

Session 5--Field Cases, Stability, Support (Underground and Surface Mining)

Ballroom B 10:45 a.m. - 12:00 noon

Session Coordinator: Joe Carvalho; Chairs: Joe Carvalho, Brent Corkum

10:45 Simulations of roof collapse and cave development using a hybrid finite/discrete approach, D. Elmo, 472

11:00 Impact of longwall mining on highways, J.J. Gutiérrez, 151

11:15 Geomechanical Numerical Modelling Workflow for Large Open Pits Applied to Retro-Analysis of the East Wall of Toquepala Mine, J.L. Carvalho, 193

11:30 Estimating the Squeeze Potential For Long, Deep Tunnels Beneath the Santa Ana Mountains of Southern California, A.S. Williams, 227

11:45 Use of Levels in Underground Research Laboratories for Earth Sciences and Geotechnical Studies, J.S.Y. Wang, 276

Session 6--Salt Geomechanics I: Laboratory and Modeling

Ballroom C 10:45 a.m .- 12:00 noon

Session Coordinator: Frank Hansen; Chairs: Gary Callahan, Frank Hansen

10:45 Benchmarking of Geomechanical Constitutive Models for Rock Salt, A. Hampel, 287

11:00 Coupled Thermal-Mechanical Analyses of a Generic Salt Repository for High Level Waste, C.M. Stone, 180

11:15 Salt barrier integrity during gas pressure build-up in a radioactive waste repository–Implications from lab and field investigations, Till Popp, 493

11:30 Application of the Multi-Mechanism Deformation Model for Three-Dimensional Simulations of Salt Behavior for the Strategic Petroleum Reserve, S.R. Sobolik, 403

11:45 The Excavation Damaged Zone in Rock Salt: Outcome of the EC Project THERESA, K. Wieczorek, 384

Special Presentation, Ballroom C 12:00 noon-12:20 p.m.

Charles Fairhurst, "Looking Forward"

SYNOPSIS:

The author will briefly review the evolution of rock mechanics in the USA since the first US Symposium and some current developments in 'subsurface engineering." The purpose of the short presentation is to stimulate discussion of current trends, and perhaps to identify additional Grand Challenges in Earth Resources Engineering.

BIOGRAPHY:

The author has been involved in rock mechanics, both in the US and internationally, since 1956, the year of the first US Rock Mechanics Symposium. He is currently Chair of a Committee of the Earth Resources Engineering section of the US National Academy of Engineering charged with identifying the top five or so Grand Challenges in Earth Resources Engineering. A Grand Challenge has been defined by NAE President Vest as one that is "visionary, but do-able with the right influx of work and resources over the next few decades;" - a challenge that, if met, would be "game-changing" and have a "transformative" effect on technology. Transparent Earth, i.e., making the structure of opaque solid earth visible, is one example of a Grand Challenge, the aim being, in effect, to do for Earth Resource Engineering what "imaging technologies" have done for medicine. Dr. Fairhurst is a Fellow of the American Rock Mechanics Association. Institute.

ARMA Committee on Publications Meeting, Cheyenne Room 12:20 p.m.-1:00 p.m.

Luncheon/ Exhibits Open, Ballrooms A and B 12:30 p.m.-1:40 p.m.

Sponsored by Agapito Associates, Inc.

Luncheon Speaker: John Hudson, "Rocky Rambles through Caves, Cathedrals and Caverns"

BIOGRAPHY:

John A Hudson, BSc, PhD, DSc, FREng, obtained his BSc degree in Mining Engineering from the Heriot-Watt University in Edinburgh, Scotland, in 1965 and his PhD in rock mechanics from the University of Minnesota, USA, in 1970. After a further two-year period of post-doctoral study at the University of Minnesota, from 1972-1977 he worked in the Tunnels Division at the Transport and Road Research Laboratory, UK. Then, from 1977-1979 at the Department of Strategic Research Operations in the Department of the Enviroment, UK, from 1979-1980 as a Visiting Professor at the University of Wisconsin, USA, and from 1980-1983 at the Building Research Station, UK. During this latter period, he was awarded the DSc degree by the Heriot-Watt University. From 1983 to the present, he has been affiliated as Reader and then Professor in the Department of Earth Science and Engineering at the Imperial College of Science, Technology and Medicine, University of London, UK. He was elected as a Fellow of the Royal Academy of Engineering in 1998. Also and since 1985, Professor Hudson has acted as an independent consultant on more than 100 projects.

Dr. Hudson is currently the President of the International Society for Rock Mechanics. He is a Fellow of the American Rock Mechanics Association. He also holds Adjunct/Visiting/Honorary Professor positions at the Royal Institute of Technology, Stockholm, Sweden, the Chinese Academy of Sciences, Wuhan, China, and Hong Kong University. He has been the Editor of the International Journal of Rock Mechanics & Mining Sciences since 1983, and also currently edits Elsevier's Geo-Engineering Book Series. He has authored/co-authored four books and more than 150 technical papers, plus a further three edited books, including "Comprehensive Rock Engineering" (5 vols, 4407 pages) which is the only international benchmark overview of all aspects of rock engineering. His research interests cover the whole field of rock mechanics, but are currently concentrated on systems approaches, especially via 'intelligent' rock mechanics, and radioactive waste disposal.

PODIUM PRESENTATIONS

Session 7--Rock Characterization Ii: In-Situ Characterization

Ballroom A 1:45 p.m. - 3:00 p.m.

Session Coordinator: David Yale; Chairs: Russ Maharidge, Brian Crawford

1:45 In-Situ Shear Strength of Rock-Concrete Contact Surface at the Abutments of a Concrete Dam, M. Gharouni Nik, 266

2:00 Relationship between Physical, Chemical, and Mineralogical Properties and Cohesion of Questa Rock Pile Materials , K. Boakye , 165

2:15 Numerical algorithm for constructing 3D initial stress field matching field measurements, A.I. Madyarov, 324

2:30 Interpretation of In-situ Stress at Baihetan Project, G.T. Meng, 121

2:45 Comparison of sonic fast-shear azimuth and breakout directions as stress indicators and implication for stress estimation, Romain Prioul, 145

Session 8--Dynamics I: Induced Seismicity

Ballroom B 1:45 p.m. - 3:00 p.m.

Session Coordinator: Cezar Trifu; Chairs: Erik Westman, Marisela Sanchez

1:45 Fracturing of Dry Porous Rock by Fluid Injection, S. Stanchits, 233

2:00 Stimulated Fractured Reservoir DFN Models Calibrated with Microseismic Source Mechanisms , S.C. Williams-Stroud, 520

2:15 Enhanced Imaging of Hydraulic Fracturing through Induced Seismicity, W.S. Pettitt, 274

2:30 Geometrical and Inhomogeneous Raypath Effects on the Characterization of Open-pit Seismicity, C. Trifu, 406

2:45 The Role of Chemical Compaction in the Evolution of Permeability and Strength in Granular Aggregates, Baisheng Zheng, 475

Session 9--Salt Geomechanics II: Case Studies

Ballroom C 1:45 p.m. - 3:00 p.m.

Session Coordinator: Frank Hansen; Chairs: Tom Pfeifle, Andreas Hampel

1:45 Geomechanics applied to the well design through salt layers in Brazil: A History of success, A.M. Costa, 239

2:00 Controls on in-situ stresses around salt bodies, P.F. Sanz, 169

2:15 Crushed Salt Reconsolidation at Elevated Temperatures, D.J. Clayton, 236

2:30 Final Disposal in Rock Salt-Geomechanical Assessment of the Barrier Integrity, Wolfgang Minkley, 492

2:45 Challenges Faced to Execute Hydraulic Fracturing in Brazilian Pre-Salt Wells, C.T. Azevedo, 212

DUSEL Cavern Design Group Meeting, Cheyenne Room 2:00 p.m. - 5:00 p.m.
By invitation

FLOOR POSTER PRESENTATIONS

Coffee and Posters/Exhibits Open, Ballroom Reception 3:00 p.m. - 4:00 p.m.

Floor presentations of posters in the Idaho and Arizona Rooms - Sponsored by ConocoPhillips

007 Lab Test of Brittle Behavior of Marble Sampled at Great Depth of Jinping II Hydropower Project, W.J. Chu

107 Laboratory Testing on Pierre Shale for CO2 Sequestration under Clayey Caprock, Xuejun Zhou

112 A Theoretical Explanation for Splitting of Stressed Rock Under Axial Unloading Condition, P.X. Fan

116 Analysis on Geological Factors Having Impact on Deformation of Surrounding Rock Masses of Large Cross-section Highway Tunnels, Hui-jun Yang

118 Design support for intersection of underground openings, Boris, Amusin

119 Numerical evaluation of cavern layout design for the Baihetan Hydropower Project in China, Y.L. Jiang

126 Behavior of marble at Jinping II Project--Part 1: intact Rock, Z.G. Shan

137 Stability Analysis of Rock Slopes Using Block Theory, Haswanto Haswanto

160 A New Device for Measuring In-situ Stresses by Using Acoustic Emissions in Rocks, L. Fa

161 Equivalent continuum modeling for wave propagation in jointed rock masses, Oleg Vorobiev

166 Study on high speed slide mechanism of Qianjiangping landslide in China Three Gorges Reservoir, Xiao Shi-rong

168 Research on the Mechanism of the Floor Heave Caused by Grouting Pressure and Its Numerical Simulation, Rentai Liu

173 Deriving Rock Mechanical Properties Using Resistivity Log Data, C. Santana

184 A Safety Study of Transition Segments for A Branched Tunnel, Li-Yuan Yu

187 Mechanical Properties, Flow Properties, and Heterogeneous CO2 Sorption in Confined Powder River Coal Cores, S.A. Jikich

201 Geomechanical Modeling of a Reservoir-Scale Fault-Related Fold: The Bargy Anticline, France, K.J. Smart

211 Development of borehole jack fracturing technique for crustal stress measurement, T. Yokoyama

216 Geomechanical study for stability and land protection evaluation at a large quarry site, M. Cravero

224 Estimating In Situ Stress Magnitudes and Orientations in an Albertan Field in Western Canada, R. Teichrob

226 CO_2 Injection Evaluation in the Arbuckle Formation under Thrall-Aagard Reservoir in Kansas, Shik Han Weon

234 Hydraulic Fracture Optimization for High Deviated Wells in an Thin Turbidites Sandstone Formation in Soledad Field, Chicontepec Basin, Mexico, C. Rabe

240 Feasibility Study of Underground Coal Gasification Combined with CO_2 Capture and Sequestration in Williston Basin, North Dakota, Peng Pei

252 Finite Volume Numerical Analysis of Rock Joint Geometry Effect on the Penetration Length of Grout under the Transient Flow, J. Khani

253 Ultimate Bearing Capacity of Jointed Rocks as Homogenous Media, A. Fahimifar

260 Chemo-mechanical Effects of Rock-Fluid Interactions, Joshua C. Thompson

285 Is that Frac Job Really Breaking New Rock or Just Pumping Down a Pre-Existing Plane of Weakness?—The Integration of Geomechanics and Hydraulic-Fracture Diagnostics, Mike Mullen

316 Contact Theory for Deformable Blocks in Three-Dimensional Discontinuous Deformation Analysis (3-D DDA), S.A.R. Beyabanaki

378 Micro-indentation tests to evaluate micro-scale mechanical properties of granites, H. Araki

436 A Geomechanical Model of the Bakken Petroleum System, J.B. Havens

453 Biot Critical Frequency Applied as Common Friction Factor for Chalk with Different Pore Fluids and Temperatures, K.A. Andreassen

454 The Role of Chemical Compaction in the Evolution of Permeability and Strength in Granular Aggregates, Baisheng Zheng

508 Consideration of Dilatancy Angle in the Ground Response Curve of Rock Masses, A.R. Kargar

514 Splitting failure criterion and its application in Pubugou underground cavern groups of China, Xiaojing Li

PODIUM PRESENTATIONS

Session 10--Rock Characterization III: Logging and Laboratory Correlations

Ballroom A 4:00 p.m. - 5:45 p.m.

Session Coordinator: Gang Han; Chairs: Andy Hawthorn, Fersheed Mody

4:00 Pressure solution models for quartz materials: Micromechanical development and potential impact in fractured reservoirs, J. Taron, 422

4:15 Statistical Analysis of the Effects of Mineralogy on Rock Mechanical Properties of the Woodford Shale and the Associated Impacts for Hydraulic Fracture Treatment Design, Khodir Aoudia, 303

4:30 A comparison of the normal stress and hydraulic conductivity coupling for fractures in the laboratory and in-situ, C.D. Martin, 443

4:45 Mechanical and acoustical properties of sand-clay mixtures under stress, M.H. Bhuiyan, 404

5:00 Quantifying and linking Shale properties at a variable scale, E. Diaz, 272

5:15 Petrophysical Methodology for Predicting Compressive Strength in Siliciclastic "sandstone-to-shale" Rocks, B.R. Crawford, 196

5:30 Comparison of Methods to Derive Rock Mechanical Properties from Formation Evaluation Logs, B. Woehrl, 167

Session 11--Wellbore Stability I

Ballroom B 4:00 p.m. - 5:45 p.m.

Session Coordinator: Gang Han; Chairs: Gang Han, Mohamad Khodaverdian

4:00 A Geomechanical Approach to Enhancing Well Design and Increasing Drilling Performance in the Sichuan Xinchang Gas Field, China, Shize Wang, 153

4:15 Changing the Safe Drilling Window with Invert Emulsion Drilling Fluids: Advanced Wellbore Stability Modeling Using Experimental Results, Terry Hemphill, 283

4:30 The Impacts of Failure Criteria and Geological Stress States on the Sensitivity of Parameters in Wellbore Stability Analysis, Minh H. Tran, 328

4:45 Evaluation of Consolidation and Material Yielding during Underbalanced Drilling Well in Shale - A Numerical Study, M.A. Islam, 433

5:00 Mechanical Behavior of Concentric Casing, Cement, and Formation Using Analytical and Numerical Methods, H. Jo, 142

5:15 The Effect of Horizontal Completions on the Breakdown Pressures of Anisotropic Gas Shales, C. Deenadayalu, 477

5:30 Stability Analysis in Shale through Deviated Boreholes using the Mohr and Mogi-Coulomb Failure Criteria, M.A. Islam, 432

Session 12--Coupled Processes I

Ballroom C 4:00 p.m. - 5:45 p.m.

Session Coordinator: Quan Guo; Chairs: Chung Song, Ahmad Ghassemi

4:00 Simulation of Fluid Flow in a Naturally Fractured Poro-thermoelastic Reservoir, Q. Tao, 292

4:15 3D Poroelastic Analysis of Natural Fracture Response to Variable Injection/Extraction Rates, M.R. Safari, 327

4:30 A Chemo-poroelastic Solution for Pore Pressure Transmission Test Considering Solute Diffusion, Jian Huang, 337

4:45 A multi-scale micromechanics framework for shale using nano-tools, J.A. Ortega, 480

5:00 Stabilization procedures in coupled poromechanics: A critical assessment, M. Preisig, 455

5:15 Mechanisms for permeability evolution in fracture networks: hydrothermal effects in enhanced geothermal systems, J. Taron, 423

5:30 Shaped Charge Penetration into Stressed Rock – Penetration Depth Experiments and Modeling, J. Harvey, 305

ASCE Rock Mechanics Committee Meeting, Cheyenne Room 5:45 p.m. - 6:30 p.m.

Recess for the Day 5:45 p.m.

Open Agenda

ARMA Fellows Annual Meeting, 6:30 p.m. - 9:00 p.m.

By invitation

TUESDAY, JUNE 29TH

Registration, Main Floor-Coat Room 7:00 a.m. - 5:30 p.m.

Speakers' Ready Room, Registration Desk 7:00 a.m. - 5:30 p.m.

Speakers' Breakfast, Arizona Room 7:15 a.m. - 8:20 a.m.

PODIUM PRESENTATIONS AND INVITED LECTURES

Session 13--Rock Characterization IV: Fracture Mechanics--Analytical and Numerical

Ballroom A 8:30 a.m. - 10:15 a.m.

Session Coordinator: Antonio Bobet; Chairs: Hide Yasuhara, Takatoshi Ito

Invited Speaker: Erling Fjær, "When will smart software replace measurements completely, for estimation of geomechanical parameters?"

8:30 a.m. - 8:55 a.m.

BIOGRAPHY:

Erling Fjær is a Chief Scientist at SINTEF Petroleum Research, and an Adjunct Professor in Petroleum Technology and Applied Geophysics at the Norwegian University of Science and Technology. He also holds a PhD in physics from the same university. For the last 25 years, he has been working on topics related to rock mechanics and rock acoustics for petroleum applications. His work includes co-authoring of the textbook "Petroleum Related Rock Mechanics."

9:00 A Nanomechanical Investigation of the Crack Tip Process Zone, Z. Brooks, 309

9:15 Numerical Analysis of Multiple Fracture Propagation in Heterogeneous Rock, K.S. Min, 363

9:30 Fracture Re-Initiation as a Possible Branching Mechanism during Hydraulic fracturing, Arash Dahi Taleghani, 278

9:45 Comparison between elasto-plastic and rigid-plastic cohesive surface elements and embedded strong discontinuity finite element implementation of rock fracture, R.A. Regueiro, 473

10:00 Numerical analyses of the effect of heterogeneities on rock failure process , B. Valley, 468

Session 14--Fracturing

Ballroom B 8:30 a.m. - 10:15 a.m.

Session Coordinator: John McLennan; Chairs: Claudia Santana, Reginald Hammah

Invited Speaker: Will Bawden, "Thoughts on Quantitative Field Scale Characterization of Post-failure Rock Mass Conditions and the Influence on Underground Mine Design
Using a Canadian Mining Case Study" 8:30 a.m. - 8:55 a.m.

SYNOPSIS:

Field scale rock mass constitutive behaviour remains an area of intense debate. The Generalized Hoek-Brown [GHB] criterion remains the most popular and commonly used rock mass behavior criteria for practical applications. The GHB as originally developed did not did not incorporate post-peak behavior and provides no guidance as to how such parameters should be derived. It is, in fact, uncertain whether derivation of so called post-peak GHB parameters is a valid or appropriate approach, although at present there appear to be few viable alternate options. Numerous attempts have been made to derive post-peak GHB parameters and to use these to model rock mass behavior in the post failure regime. This paper critically discusses several of these approaches and tests two of these against two field case

BIOGRAPHY:

Will Bawden is the Pierre Lassonde Chair in Mining Engineering and Chair, Lassonde Mineral Engineering Program on the Faculty of Applied Science and Engineering, Department of Civil Engineering, University of Toronto. He is also a consultant on geomechanical mine design and ground control to several major mining companies.

9:00 Uncertainty in Estimation of Volumetric Block Proportion of Bimrocks by Using Scanline Method, Y.M. Tien, 158

9:15 The Effect of Different Rock Types and Roller Cone Insert Types and Wear on ROP (Rate of Penetration), A. Wu, 207

9:30 Cohesive Fracture Mechanics Based Analysis to Model Ductile Rock Fracture, Yao Yao, 140

9:45 Modeling surface heave induced by hydraulic fracturing stimulation and CO_2 injection into coal seams, H. Li, 319

10:00 Improved Fracture Gradient Methodology — Understanding the Minimum Stress in Gulf of Mexico, Gemma Keaney , 177

Session 15--Numerical Modeling--Fractures

Ballroom C 8:30 a.m. - 10:15 a.m.

Session Coordinator: Bill Dershowitz; Chairs: John Harrison, Bill Dershowitz

Invited Speaker: Brian McPherson, "Lessons Learned from Ongoing Field Tests of Geologic CO_2 Sequestration"

SYNOPSIS:

International concern about climate change is rising. It is clear that a single approach to solve the global carbon emissions problem, the proverbial "silver bullet," does not exist. Rather, a portfolio of options must be deployed. One element of such a portfolio is to capture carbon dioxide during or after the fossil fuel combustion process, and sequester the CO2 below the earth's surface in deep rock formations. Three primary types of such geologic carbon sequestration are possible, in general: (1) injection and storage in oil and gas reservoirs, (2) injection and storage in coal beds, and (3) injection and storage in deep brine aquifers. At the time of this conference, over 25 geologic sequestration field tests were at various stages of design and deployment in the U.S. Two field tests are ongoing in the southwestern United States, and research associated with these tests has yielded some important lessons associated with geomechanical processes, especially induced seismicity:

- In all cases, it is difficult to predict geomechanical processes;
- In all cases, it is difficult to predict induced seismicity;
- Microseismicity - both natural and induced - occurs just about everywhere, but most seismic/micro-seismic events are associated with pre-existing faults and low permeability zones;
- Microseismicity can aid in identifying geologic features like "critically-stressed" faults;
- Induced seismicity can be controlled through effective reservoir/injection engineering; and
- Careful and effective site characterization and selection are keys to successful microseismicity management.

BIOGRAPHY:

Brian McPherson is an Associate Professor of Civil and Environmental Engineering at the University of Utah. Since 1997, Dr. McPherson has conducted carbon management and engineering research, especially geological sequestration studies. Technical focus areas include groundwater and reservoir simulation, multiphase flow analysis and simulation, rock deformation, and subsurface chemically reactive transport analysis and simulation.

9:00 A New Approach to Hydraulic Fracturing Modeling in Naturally Fractured Reservoirs, Branko Damjanac, 400

9:15 Pore Distribution and Statistical Size Effect: a Discrete Element Analysis, A.E. Gharahbagh, 322

9:30 A numeric simulation of rock avalanches using the combined finite-discrete element method, FEMDEM, J. Xiang, 388

9:45 A damage and fracture model for jointed rock masses and application in stability analysis on an underground cavern group, Kui Zhou, 150

10:00 Analysis of sand production processes at the pore scale using the discrete element method and lattice Boltzman procedures, Raquel Quadros Velloso, 221

Tour: Downtown Salt Lake City, Temple Square 10:00 a.m. - 3:00 p.m.

Assemble in Hotel Lobby at 9:45 a.m.

Coffee Break/Exhibits Open, Ballroom Reception 10:15 a.m. - 10:45 a.m.

Sponsored by Advantek International

PODIUM PRESENTATIONS

Session 16--Discontinuities I

Ballroom A 10:45 a.m. - 12:00 noon

Session Coordinator: Antonio Bobet; Co-Chairs: Steve Laubach, John Kemeny

10:45 Intrastratal and Suprastratal Deformation Associated with Collapsed-Paleocave Systems, R.G. Loucks, 141

11:00 Using empirical trends in fracture size-frequency data to constrain subsurface fracture abundance, J.N. Hooker, 325

11:15 Stability of Rock Blocks Subjected to High-Velocity Water Jet Impact, P. Asadollahi, 203

11:30 A Improved K-means Clustering Method for the Automatic Grouping of Discontinuity Sets, L.N.Y. Wong, 265

11:45 Techniques for Identification and Prediction of Mechanical Stratigraphy in Fractured Rock Masses, P.R. La Pointe, 296

Session 17--Injection and Depletion

Ballroom B 10:45 a.m. - 12:00 noon

Session Coordinator: Rico Ramos; Chairs: Koji Yamamota, Ion Ispas

10:45 Modeling of the Hydraulic Fractures in Unconsolidated Oil Sands Reservoir, B. Xu, 123

11:00 Finite Element Modeling of Rock Cutting, M.C. Jaime, 231

11:15 Injectivity and Fracturing in Unconsolidated Sand Reservoirs: Waterflooding Case Study, Offshore Nigeria, M. Khodaverdian, 139

11:30 Hydraulic fracture propagation in pre-fractured natural rocks , C. Meng, 318

11:45 Stress Evolution due to Depletion in an Ellipsoidal Elasto-Plastic Reservoir, V.A. Dunayevsky, 304

Session 18--Numerical Modeling - Petroleum Geomechanics

Ballroom C 10:45 a.m. - 12:00 noon

Session Coordinator: Bill Dershowitz; Chairs: Ivan Gil, Alexei Savitski

10:45 On the importance and computation of cohesive force contribution to the total potential energy in 3D-DDA, S.A.R. Keneti, 106

11:00 Three-Dimensional Fracture Simulation using the Virtual Multidimensional Internal Bond, Z.Z. Zhang, 523

11:15 Numerical Determination of Representative Volume Element of Rock, A.E. Gharahbagh, 131

11:30 Development of Virtual Geoscience Simulation Tools, VGeST for irregular blocky rock applications in rock engineering using the combined finite discrete element method, FEMDEM, J-P. Latham, 389

11:45 A confinement and deformation dependent dilation angle model for rocks, M.Cai, 459

Special Presentation, Ballroom C 12:00 noon -12:20 p.m.

Derek Elsworth, "DUSEL: Status Update and Prognosis"

SYNOPSIS:

The Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake presents unique opportunities for subsurface science and engineering in a broad array of disciplines. We will discuss the evolution, status and opportunities afforded by this initiative with a particular emphasis on how it impacts this - the geomechanics - community.

BIOGRAPHY:

Derek Elsworth is a professor in Energy and Mineral Engineering and in the Center for Geomechanics, Geofluids and Geohazards at Penn State. His principal interest is in the role of fluids in natural processes and in the performance of reservoirs and repositories with an emphasis on the effects of coupling between complex phenomena.

Luncheon/ Exhibits Open, Ballroom A & B 12:30 p.m.-1:40 p.m.

Sponsored by ConocoPhillips

Luncheon Speaker: David Hall, "Diamond is man's best friend"

Mr. Hall will explain how the invention of man-made diamond enabled our modern economy including large increases in the productivity of drilling.

BIOGRAPHY:

David R. Hall has been involved in the Man Made Diamond industry since its beginnings. His father, Dr. H. Tracy Hall was the lucky scientist who made the discovery while working for General Electric in December of 1954. Mr. Hall is the president of Novatek, a Provo Utah company with 200 employees. Novatek received over 70 patents last year that were primarily in the field of drilling technology. Mr. Hall's professional goal is to decrease the cost of drilling so that the capacitance and the heat of the earth becomes our primary energy sink and source.

PODIUM PRESENTATIONS

Session 19--Discontinuities II

Ballroom A 1:45 p.m .- 3:00 p.m.

Session Coordinator: Antonio Bobet; Chairs: Joe Morris, Euripides Vargas

1:45 3D Poroelastic Analysis of Rock Failure around a Hydraulic Fracture, A. Ghassemi, 506

2:00 Modeling of Near-Surface Bowl-Shaped Fractures, E. Gordeliy, 155

2:15 Stress heterogeneity in a fractured rock mass modeled with the combined finite-discrete element method, J.P. Harrison, 390

2:30 Limits of Applicability of the Finite Element Explicit Joint Model in the Analysis of Jointed Rock Problems, A. Riahi, 336

2:45 Crack localization and characterization in solid media using time reversal Techniques, B.E. Anderson, 154

Session 20—Geophysics and Monitoring: Acoustics and Tomography

Ballroom B 1:45 p.m. - 3:00 p.m.

Session Coordinator: Alvin Chan; Chairs: Alvin Chan, Rune Holt

1:45 A new model for long-distance movement of earthquake induced landslide, G. Chen, 297

2:00 Split Hopkinson Resonant Bar test and its application for seismic property characterization of geological media, S. Nakagawa, 491

2:15 Seismic Wavespeed used to Approximate Rock Mass Quality in Unweathered Sandstone, N.H. Putnam, 504

2:30 The Reflectivity and Transmissivity of Anisotropic Materials: A Physical Modeling Study, M. Ortiz-Osornio, 330

2:45 Woodford Shale Mechanical Properties and the Impacts of Lithofacies, R. Sierra, 461

Session 21—Coupled Processes II

Ballroom C 1:45 p.m. - 3:00 p.m.

Session Coordinator: Quan Guo; Chairs: Sau-Wai Wong, Neal Nagel

1:45 Reservoir depletion effect on In-situ Stresses and Mud Weight Selection, Fanhong (Frank) Meng, 342

2:00 Evaluation of validity of cubic law and hydro-mechanical properties of rock fracture using coupled shear-flow tests and 3-D numerical simulation, B. Li, 2412:15 Relations between Coal Permeability and Directional Strains and Their Application to San Juan Basin, Zhongwei Chen, 245

2:30 Analysis of fracture mechanical behavior under normal stress, J. Jocker, 152

2:45 Analytical and numerical analysis of fluid flow through rough natural fracture profiles, A. Hosseinian, 218

FLOOR POSTER PRESENTATIONS

Coffee and Posters/Exhibits Open, Ballroom Reception 3:00 p.m. - 4:00 p.m.

Floor presentations of posters in the Idaho and Wyoming Rooms - Sponsored by ConocoPhillips

125 Study of characteristics of an excavation damaged zone around deeply buried tunnels under blasting conditions, P. Yan

127 Behavior of marble at Jinping II Project--Part 2: rockmass, C.S. Zhang

144 Geotechnical safety program for underground storage caverns in salt, Lianyang Zhang

171 Inverting for creep strain parameters of uncemented reservoir sands using arbitrary stress-strain data, P.N. Hagin

188 Field test study on the reflection laws of seismic waves on the large-scale underground water-bearing body, Xiao Zhang

204 Rock Fragmentation Module in 3-D Rock-fall Analysis, Y. Wang

205 Measurement of Fracture Aperture in Granite Core Using Microfocus Xray CT, S. Nakashima

248 A DEM Study on Perforation Induced Damaged Zones and Penetration Length in Sandstone Reservoirs, Amin Nabipour

254 Comparative Study Using Rock Energy and Drilling Strength Models, B. Rashidi

273 Microseismic validation of jointed rock models in cave mining, J.M. Reyes-Montes

298 Investigation into the Stability of Rocks Surrounding Gateway Affected by Coal Pillar Width in Deep Mining, Ke Yang

300 Test Study On The Changing of the Porosity for Water-Saturated Granular Shale During its Creep, Zhan-guo Ma

301 A Case Study on Translational Failure of Sedimentary Cut-Slopes in Korea, Seung Hyun Kim

302 The Influence of a weak structure instability of a deep rock roadway subjected to a stress wave, Ai-hong Lu

326 The Effect of Boundary Conditions on the Creep Behavior of Salt Rock using Numerical Modeling, M. Jafari

341 Slope stability at Chador Malu and optimization of the monitoring systems, S. Aloodari

352 A general investigation on slope stability at Khersan III hydropower plant using numerical modeling, M.A. Jafari

353 Prediction of Standard Penetration Tests via Microtremor Array Using Artificial Neural Networks, S. Angorani

371 Crustal Deformation History of the Tsushima Island and its Vicinity, Japan, During the Cenozoiz Teritiary, Honggyun Kim

391 Open Pit and Underground Mine Interaction with Phase2, E.A. Cordova

429 Influence of Groove Geometry and Cutter Inclination in Rock Cutting, T. Richard

431 Digital Image Correlation and the Fracture Process in Rock, Qing Lin

470 Geomechanical Data Acquisition and Modeling Applied to an Offshore Sandstone Petroleum Reservoir, L.C. Sousa, Jr.

474 Stress Effect On Compressibility Of Weakly Anisotropic Micro-Fractured Rocks a Study Case On Colombian Foothills Tight Sandstones, J.M. Carvajal

476 Water Imbibition in Oilfield Rocks: Experimental Data and Comparison to Theoretical Models, Martin Webiao-Suarez

481 Top coal deformation characteristics of high section fully-mechanized top-coal caving for extra-steep-thick seam, S.J. Miao

487 Development of a damage-based constitutive model for brittle rocks, A. Mortazavi

495 Advanced Strain–Hardening Approach Constitutive model for rock salt describing transient, stationary, and accelerated creep and dilatancy, Ralf-Michael Günther

507 A Sensitive Analysis on Mohr-Coulomb and Hoek-Brown Parameters Effective in Ground Response Curve, A.R. Kargar

510 Numerical Modeling of Mechanical Behavior of a Jointed Rock Mass, M. Asadizadeh

512 Large Scale Experiment Study on Reinforcement Effect of Rock Bolt to Intermittent Jointed Rock Mass, W.M. Yang

515 Numerical simulation of Large Diameter Bored Pile of High Pressure Jet Grouting, Jin Li

527 A Neural Network Approach for Predicting the Penetration Depth during Laser Perforation in Limestone, R. Keshavarzi

PODIUM PRESENTATIONS

Session 22--Underground Mining

Ballroom A 4:00 p.m. - 5:45 p.m.

Session Coordinators: Hani Mitri, James Donovan; Chairs: Hani Mitri, John Henning

4:00 Ground support practices for low quality rock–with illustrative examples, J.G. Henning, 317

4:15 Mining Strategies of Multi-Sill Pillars in Burst Prone Ground Conditions at Vale Inco's Coleman Mine, Z. Hosseini, 456

4:30 Assessment of haulage drift enhanced support system--a case study, W. Wei, 458

4:45 Examining the influence of stope strike length on unplanned ore dilution in narrow vein longitudinal mining, R. Hughes, 392

5:00 Rock excavation and support for a crusher hall at Rana Gruber, Norway, Q.N. Trinh, 113

5:15 Finite Deformation Analysis of Displacement Field Around a Deep Tunnel, Y.N. Gao, 517

5:30 Rockburst at Jinping II Tunneling Project, H.C. Zhu, 122

Session 23--Dynamics II: Drilling/Cutting Mechanics

Ballroom B 4:00 p.m. - 5:45 p.m.

Session Coordinators: Gang Han and Quan Guo; Chairs: David Curry, Haiying Huang

4:00 Cutting Action of Impregnated Diamond Segments: Modelling and Experimental Validation, L.F.P. Franca, 439

4:15 A New Drilling Rate Model for Tricone Bits and Its Application to Predict Rock Compressive Strength, G. Hareland, 206

4:30 Discrete Element Modeling of Rock Cutting Using Crushable Particles, J.A. Mendoza, 232

4:45 Experimental Investigation of Bit Vibration on Rotary Drilling Penetration Rate, Heng Li, 426

5:00 Thick PDC, Shaped Cutters for Geothermal Drilling: A Fixed Cutter Solution for a Roller Cone Drilling Environment, C.J. Durrand, 524

5:15 Modeling Percussive Drilling Performance using Simulated Visco-Elasto- Plastic Rock Medium, M.S. Sazidy, 434

5:30 Pillar Stability Assessment Approach for Mechanized and Drill and Blast Excavations, N. Bahrani, 289

Session 24--Thermal Geomechanics

Ballroom C 4:00 p.m. - 5:45 p.m.

Session Coordinator: David Yale; Chairs: Balin Wu, Nathan Deisman

4:00 Study of Geomechanics in Engineered Geothermal Systems, S.M. Johnson, 250

4:15 Predicting the Spatial Extent of Injection-Induced Zones of Enhanced Permeability at the Northwest Geysers EGS Demonstration Project, J. Rutqvist, 502

4:30 Thermally-Induced Tensile Fractures in the Barnett Shale and Their Implications to Gas Shale Fracability, Dung T. Tran, 466

4:45 Rock Mechanical Testing for the Desert Peak Enhanced Geothermal System (EGS) Project, Nevada, Susan Juch Lutz, 313

5:00 Geomechanical Stability during CH4 Production from Hydrates– Depressurization or CO2 Sequestration with CO2-CH4 Exchange, K.A. Birkedal, 321

5:15 Stirred-Flow-Through Experiments of Granite under Temperature and pH Conditions Controlled, H. Yasuhara, 156

5:30 Probabilistic Analysis of Shear Slip of Fractures Induced by Thermomechanical Loading in a Deep Geological Repository for Nuclear Waste, Jaewon Lee, 208

Awards Reception and Banquet, Grand Ballroom **7:00 p.m. - 9:30 p.m.**

Induction of new ARMA Fellows John Hudson and Wolfgang Wawersik; receipt of Fellow Medal for Priscilla Nelson.

2010 ARMA Awards

2011 US Rock and Geomechanics Symposium

WEDNESDAY, JUNE 30TH

Registration, Main Floor-Coat Room 7:00 a.m. - 1:15 p.m.

Speakers' Ready Room, Registration Desk 7:00 a.m. - 3:15 p.m.

Speakers' Breakfast, Arizona Room 7:15 a.m. - 8:20 a.m.

PODIUM PRESENTATIONS AND INVITED LECTURES

Session 25--Weak Rocks and Shales

Ballroom A 8:30 a.m. - 10:15 a.m.

Session Coordinator: Rico Ramos; Chairs: Adolfo Polillo, Marte Gutierrez

Invited Speaker: David Yale, "Large-Scale Laboratory Testing of the Geomechanics of Petroleum Reservoirs"

SYNOPSIS:

A large-scale laboratory for testing a wide range of petroleum recovery and geomechanical processes has been designed and built to provide a test bed for understanding processes before proceeding to field-scale trials of new technology. The system, dubbed LARGE for Large-scale Apparatus for Reservoir and Geomechanical Experimentation, is centered around a 50 ton, 2100 psi rated pressure vessel that allows testing of processes on a "physical model" of the reservoir that is 210 cm in diameter and up to 50 cm thick. Key specifications for the system include an "overburden" spacer to mimic the deformation of the real overburden on the reservoir, pumps and "feed" vessels to simulate injection and production in up to 10 wells, over 450 sensors to measure and image real-time the progress of processes occurring in the vessel, a cooling and heating system to control the temperature of the sandpack between -30 ºC and +90 ºC, and a computer-controlled lab control system to automatically run most processes and collect and process huge amounts of data. They system can be used for a wide range of processes but early work will focus on reservoir processes in shallow, heavy oil reservoirs and overpressured unconsolidated sand reservoirs. This talk also will discuss details of how geomechanics of reservoir processes can be simulated in this system.

BIOGRAPHY:

David Yale is a Senior Research Advisor and Breakthrough Research Project Lead with ExxonMobil Upstream Research Company in Clinton, N.J. He has been with Mobil and ExxonMobil since 1985. He specializes in geomechanics, reservoir engineering, and production engineering research. His current focus is on the impact of geomechanics on the recovery of oil from the heavy oil sands in Canada. He has been a member of the Board of Directors of ARMA since 2005 and is a past President of ARMA. He was Technical Program Chair of the ARMA Symposia in 2004 and 2006.

9:00 Anisotropy, Compaction and Dispersion Characteristics of Reservoir and Seal Shales, Azra N. Tutuncu, 344

9:15 Strength, creep and frictional properties of gas shale reservoir rocks, H. Sone, 463

9:30 Strength Anisotropy of Mudstones and Shales, R.T. Ewy, 114

9:45 Relationships between Unit Weight, Unconfined Compressive Strength, and Deformation Modulus of Vesicular Basalt, B.T. Kuhn, 437

10:00 Evaluating Properties of Weak Shales in Western Missouri, N.H. Maerz, 290

Session 26--Coal Rock Mechanics

Ballroom B 8:30 a.m. - 10:15 a.m.

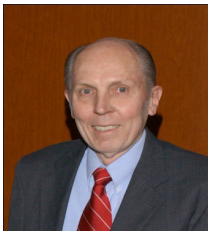
Session Coordinator: James Donovan; Chairs: Steven Brandon, Sam Spearing

Invited Speaker: Kim McCarter, "Coal Mining in Central Utah–Challenges Related to Depth and Geologic Conditions"

SYNOPSIS:

Coal production figured prominently in Utah's history. Coal mining in central Utah began with wagon mines to supply fuel for early settlers. With the introduction of rail transportation and electrical power plants, production escalated along with progressively more advanced mining methods. Today, mining is primarily done by longwall supplemented with conventional sections using continuous miners. Utah has the dubious distinction as having the highest incidence of coal "bounces" in the United States. This phenomenon is a result of unique geologic conditions and gives rise to abundant mining-induced seismicity. History, mining methods, geologic conditions, and geotechnical factors will form the focus of this presentation.

BIOGRAPHY:



Kim McCarter is a Utah native and received his Bachelor of Science and Ph.D. from the University of Utah. He began his career with Kennecott Copper Corp., at the Bingham Canyon mine where his efforts in monitoring high waste rock embankments were recognized as a major factor in improving safety of truck dumps. He accepted a full-time faculty appointment as professor of Mining Engineering at the University of Utah in 1978. From 1980 to 1982, he served as Associate Chair and acting Chair of the Mining Program and the following 26 years he served as Chair of the Mining Engineering Department. As a faculty member, he teaches required courses and has twice received the College's outstanding teaching award. He received the 1999 Faculty Award from the Old Timers Organization, was recognized as a Distinguished Member of SME in 2003, became the second person to receive the status of Honorary Member of the Rocky Mountain Coal Mining Institute in 2004, and received a Distinguished Service award from the Utah Mining Association in 2008. He serves as a member of the Technical Advisory Committee for the Utah Office of Coal Mine Safety. Currently, his research deals with seismicity in underground coal mines and topics related to mining deep coal deposits.

9:00 Evolution of Permeability in Coal to Sorbing Gases–A Preliminary Study, Shugang Wang, 279

9:15 Verification of In situ Pillar Strength for Utah Coal Seams, Hamid Maleki, 499

9:30 Swell of Coal Matrix Induced by Gas Sorption and Its Partition to Porevolume and Bulk Strains–A Critical Parameter for Coal Permeability, Meng Lu, 370

9:45 The application of and need for high density backfill on US coal mines, A.J.S. Spearing, 500

10:00 Water Fusion for Bump Control; Laboratory Feasibility Tests on Utah Coal, M.K. McCarter, 271

Session 27--Rock Stabilization

Ballroom C 8:30 a.m. - 10:15 a.m.

Session Coordinator: Bill Gates; Chairs: Bill Gates, Adam Williams

Invited Speaker: Erik Eberhardt, "Geotechnical Challenges of Deep Tunnels:

The Known Knowns, Known Unknowns, & Unknown Unknowns"

SYNOPSIS:

Recent infrastructure projects in the European Alps, South American Andes and the Himalayan Range in south Asia have called for tunnel designs with overburdens only previously encountered in deep mining. Extreme squeezing, rock bursting and high pressure water inflows have added considerably to the challenges designers face, in addition to those normally encountered with respect to geological uncertainty, and foreseen and unforeseen ground conditions. This talk will discuss these challenges providing examples from several recent deep tunneling projects where overburdens exceed 2000 m (6000 ft).

BIOGRAPHY:

Erik Eberhardt is Professor of Rock Engineering in the Geological Engineering program at the University of British Columbia in Vancouver, Canada. He has worked on a number of mining and tunneling projects worldwide, authoring over 100 technical papers. He is a registered Professional Engineer and has served as an expert reviewer and designer on a number of tunneling projects including Niagara Falls and, most recently, the Bunji Hydropower Project.

9:00 Development of a New Yielding Rock Bolt–Yield-Lok Bolt, Y.K. Wu, 197

9:15 Geotechnical considerations for design of soil nail walls in rock slopes, I-405 Freeway, Sepulveda Pass, Los Angeles, California, W.C.B. Gates, 217

9:30 Influence of corrosion rate on the capacity of rock support, J.F. Dorion, 259

9:45 Numerical Analysis of Grout Flow and Injection Pressure Affected by JRC and Aperture Size, Ki-Hwan Jeon, 331

10:00 Examination of Shotcrete Liner at Devil's Slide Tunnel Utilizing ASTM 1550 Field Test Results and Back Analysis, J.B. Decker, 402

Tour: Northern Utah - Great Salt Lake, Spiral Jetty, Nature Conservancy Sanctuary and Golden Spike Monument 9:00 a.m. - 4:00 p.m.

Meet in lobby; bus leaves 9:00 a.m. from Little America Hotel

Coffee Break/Exhibits Open, Ballroom Reception 10:15 a.m. - 10:45 a.m.

Sponsored by Advantek International

Exhibit Take Down, Ballroom Reception 10:45 a.m. - 11:30 a.m.

PODIUM PRESENTATIONS

Session 28--Unconsolidated Formations

Arizona Room 10:45 a.m. - 12:00 noon

Session Coordinator: Rico Ramos; Chairs: Lee Chin, Paul van den Hoek

10:45 Use of Volumetric Sand Production Tool on Field Data to help plan Oil Production Strategy, P.R. Cerasi, 219

11:00 Experimental Analysis of Gravel Pack Mesh Size Effect on the Screen Deformation under High in Situ Stress Contrast, F.M.G. Villarroel, 262

11:15 Sand production rate under multiphase flow and water breakthrough , E. Papamichos, 340

11:30 Geomechanics of oil sands under injection, David P. Yale, 257

11:45 Chemo-Plasticity Modeling of Pore-Fluid Induced Degradation of Soft Rocks, Marte Gutierrez, 117

Session 29--Monitoring and Remote Sensing

Idaho Room 10:45 a.m. - 12:00 noon

Session Coordinator: James Donovan; Chairs: John Kemeny, James Donovan

10:45 Detection of Surface Deformation at Mining and Geothermal Sites Using Satellite Radar Interferometry (InSAR), M. Eneva, 280

11:00 A photogrammetric approach to brittle fracture characterization in mine pillars, T.D. Styles, 410

11:15 Cell to node projections: An assessment of error, I.R. Goumiri, 457

11:30 Fiber optic strain and temperature monitoring in crystalline rock at the Sanford Underground Science and Engineering Laboratory (SUSEL), Lead, South Dakota, J.R. Gage, 367

11:45 Case study: measuring subsidence above coal mines using differential interferometric synthetic aperture radar, J. Donovan, 417

Session 30--Storage and Repositories I

Wyoming Room 10:45 a.m. - 12:00 noon

Session Coordinator: Joe Carvalho; Chairs: Jean-Claude Roegiers, Dung Tran

10:45 Risks and mitigation problems in a CO2 injection project for a petroleum onshore field in Brazil, R.A. Mendes, 162

11:00 A Study of Injection-Induced Mechanical Deformation at the In Salah CO2 Storage Project, J.P. Morris, 307

11:15 Surveillance Modeling and Operational Controls Ensure Integrity of Alaska's Grind and Inject Operations, K. Zaki, 333

11:30 3D geomechanics in UGS projects: A comprehensive study in northern Italy, N. Castelletto, 185

11:45 Study of Geomechanical Effects in Deep Aquifer CO2 Storage, David Tran, 230

Invited Speaker, Ballroom C **12:00-12:20pm**

Carolyn Ann Koh, "Natural Gas Hydrates in Energy Recovery and Transportation"

SYNOPSIS:

An overview of the state-of-the-art of natural gas hydrates will be presented. This overview will include discussions on hydrate technologies in industrial flow assurance, and the assessment of hydrates as a potential future energy source. New insight into controlling hydrate formation in these technological applications requires fundamental understanding of gas hydrate crystal growth and decomposition processes. A combination of microscopic and macroscopic techniques have been applied to study these processes. Key challenges to recovering gas from methane hydrate natural deposits in a safe and controlled manner include: more accurate assessments of the geomechanical stability of the wellbore and slope stability during production, as well as the potential environmental impact of these activities.

BIOGRAPHY:

Carolyn Ann Koh received her BSc (hons) and Ph.D. degrees from University of W. London and postdoctoral training at Cornell University. She was a Reader (Associate Professor) at King's College, London University before joining the Colorado School of Mines in 2004, where she is currently an Associate Professor in the Chemical Engineering Department and co-director of the CSM Center for Hydrate Research. She has been a visiting Professor at Cornell, Penn State and London University. She was a consultant for the Gas Research Institute in Chicago and is a Fellow of the Royal Society of Chemistry, a member of the Editorial Advisory Board of the ACS J. Chem. Eng. Data, and served on the National Academies NRC committee assessing the US DOE National Methane Hydrate Program. She has been working on hydrate research for over 15 years using spectroscopy, neutron diffraction and computer simulation techniques. This work led to her award of the Young Scientist Award of the British Association for Crystal Growth. She has received research awards totaling over $6 million as Principal Investigator, and in addition, is the PI/co-PI for research awards in excess of $1.3 million/year with the Center for Hydrate Research. She has over 90 publications in refereed journals, including Science, Physics Today, J. American Chemical Society, and a new book, Clathrate Hydrates of Natural Gases, co-authored with E.D. Sloan. C.A. Koh has received over 50 invited talks, and plenary and keynote lecture invitations from academic institutions and industrial companies (in the US, Canada, Europe, Asia) and national and international committees and conferences.

Lunch 12:30 p.m. - 1:30 p.m.

PODIUM PRESENTATIONS

Session 31--Laboratory Testing

Arizona Room 1:30 p.m. - 3:00 p.m.

Session Coordinator: John McLennan; Chairs: Paul La Pointe, Mao Bai

1:30 Experimental study on shear strength recovery of single rock fracture through slide-hold-slide direct shear test and its modeling, K. Kishida, 365

1:45 Initiation and growth of a hydraulic fracture from a borehole under toughness- or viscosity- dominated conditions, X. Zhang, 148

2:00 Quantify Uncertainty of Rock Failure Parameters from Laboratory Triaxial Testings using Conventional and Multistage Approaches, Dung T. Tran, 263

2:15 Comparisons of 2D Imaging Techniques for Internal Macropore Characterization, Nick Hudyma, 376

2:30 Effect of temperature on ultrasonic velocities of unconsolidated sandstones reservoirs during the SAGD recovery process, D.H. Doan, 195

2:45 True Triaxial Testing of Castlegate Sandstone, M.D. Ingraham, 314

Session 32--Permeability and Failure in Carbonates and Hydrates

Idaho Room 1:30 p.m. - 3:00 p.m.

Session Coordinator: Azra Tutuncu; Chairs: Max Wang, Gang Li

1:30 Effects of Self-Preservation of Natural Gas-Hydrates, Y.F., Makogon, 291

1:45 The Effects of Coupled Chemical-Mechanical Processes on the Evolution of Permeability in a Carbonate Fracture, T.P. McGuire, 471

2:00 Laboratory measurements of static and dynamic bulk moduli in carbonate, Aiman Bakhorji, 465

2:15 Determination of dynamic fracture toughness using CCNBD in SHPB testing, Ke Man, 513

2:30 Visualizing Oil Displacement in Fractured Carbonate Rocks–Impacts on Oil Recovery at Different Hydrostatic Stress and Wettability Conditions, M.A. Fernø, 288

2:45 Mechanical Behavior of a Brazilian Off-Shore Carbonate Reservoir, E.S.R. Santos, 199

Session 33-- Storage and Repositories II

Wyoming Room 1:30 p.m. - 3:00 p.m.

Session Coordinator: Quan Guo; Chairs: Thomas Geehan, Karim Zaki

1:30 Laboratory studies of the compressibility and permeability of low-rank coal samples from the Powder River Basin, Wyoming, USA , P.N. Hagin, 170

1:45 The Impact of Local Stress Field Orientation on Pressures Encountered during Waste Injection Operations in the Ivan River Field, Alaska, K. Zaki, 332

2:00 Geomechanical Modeling Techniques Applied to Waste Injection Process, Julio R. Ronderos, 397

2:15 Geomechanical Evaluation of Solids Injection, Ivan Gil, 399

2:30 Sensitivity of Storage Field Performance to Geologic and Cavern Design Parameters in Salt Domes, B.Y. Park, 380

2:45 Preliminary Numerical Analyses of Proposed DUSEL Cavities, M.C. Loken, 143

Ice Cream and Coffee Break, Outdoors 3:00 p.m. - 3:30 p.m.

Sponsored by Golder Associates

PODIUM PRESENTATIONS

Session 34--Wellbore Stability II

Arizona Room 3:30 p.m. - 5:15 p.m.

Session Coordinator: Gang Han; Chairs: Chris Ward, Dale Walters

3:30 A thermo-poro-elastic analysis of stress fields around a borehole, B. Wu, 442

3:45 Specialist Program for Injection Pressure Limits Considering Fault Reactivation Criteria, L.C. Pereira, 214

4:00 A Methodology of Root Cause Analysis of Well Bore Failure and Lost Production Using the Well Information, A. Hayatdavoudi, 357

4:15 Abnormal Pore Pressure Mechanisms in Brazil, H.L.V. Freire, 407

4:30 Long-term well integrity: a semi-analytical approach, G. Musso, 398

4:45 A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore on Damage Evolution, S.H. Lee, 228

5:00 Rethinking of Shale Swelling Based on Interesting Test Results, Hong (Max) Wang, 172

Session 35—Multidisciplinary Geomechanics

Idaho Room 3:30 p.m. - 5:15 p.m.

Session Coordinator: David Yale; Chairs: Richard Albert, Yuxing Xiao

3:30 Back analysis of Over-break in a Longhole Open Stope Operation using Non-linear Elasto-Plastic Numerical Modelling, P.M. Cepuritis, 124

3:45 Full-scale linear cutting test to study rotation of conical bit, Eunhye Kim, 181

4:00 Low Cover Considerations for the Large Tunnels on the North South Bypass Tunnel Project, Brisbane, M.R. Funkhouser, 256

4:15 Methodology of in-situ stress analysis and its application to a pumped storage hydro-power station in China, Chenghu Wang, 238

4:30 The Role of Geomechanics in the Development of an HPHT Field, S. De Gennaro, 450

4:45 A Critical Evaluation of Unconventional Gas Recovery from the Marcellus Shale, Northeastern United States, Dae Sung Lee, 440

5:00 Possible Sources of Acoustic Emission Events During Hydraulic Fracturing, A.A. Surdi, 478

Session 36—Coupled Processes III

Wyoming Room 3:30 p.m. - 5:15 p.m.

Session Coordinator: Joe Carvalho; Chairs: Gildardo Osorio, Jianlin Wang

3:30 Deformation Response of Coal Mine Slopes–Implications for Slope Hazard Management Using Evacuation Based on Slope Monitoring, N.J. Harries, 482

3:45 Development of Permeability Anisotropy during Coalbed Methane Production, Yu Wu, 246

4:00 Reactive Transport in a Planar Fracture in Hot and Poroelastic Rock, C. Rawal, 335

4:15 Controls of Permeability on the Mechanical Evolution of Shortening Basins, R. Foroozan, 375

4:30 Permeability Evolution of Gas-Infiltrated Coal under Varied Stress Paths, Ghazal Izadi, 415

4:45 Experimental Study of Heterogeneous Water Flow in a Sheared Fracture , K. Sakaguchi, 315

5:00 Cuttings Injection and Monitoring Operations: Cashiriari Gas Field, Peru, S.A. Marinello, 452

Closing Session, Ballroom C	5:15 p.m. - 5:30 p.m.
Evening Activity	6:30 p.m. - 9:00 p.m.
Haute Cuisine in Millcreek Canyon-Dinner Under the Stars	
Bus Leaves from Hotel at 6:30 p.m.; Meet in Lobby	

THURSDAY JULY 1, 2010

Field Trip: Utah Geothermal Power	7:00 a.m. - 7:00 p.m.
Bus Leave 7:00 a.m. from Little America Hotel; Meet in Lobby	

The Little America's concierge can recommend restaurants, including the following

Salt Lake City's

PREMIER RESTAURANTS

LITTLE AMERICA HOTEL GARDEN CAFE at the GRAND	-Garden Café http://www.grandamerica.com/cafe.html In keeping with the style and elegance of the Grand America Hotel, menu favorites include the freshest-produce, game, and seafood. Award winning Sunday brunch.
	-Steakhouse http://www.littleamerica.com/slc/d2.html The specialty prime rib is an absolute must. You can also choose from a variety of seafood entrees, garden fresh salads, and fine desserts.
	-Metropolitan http://www.themetropolitan.com/ The city's most innovative restaurant. Award-winning food in an award-winning setting. Large private room. 15 min. walk from hotel.
The New Yorker	-New Yorker: http://www.gastronomyinc.com Appropriately named. Classic American dishes with a contemporary flair in a sophisticated atmosphere. Very nice private rooms. 10 min walk from hotel.
PRIME STEAKHOUSE & WINE BAR Fleming's	-Flemings Steak and Wine Bar http://www.flemingssteakhouse.com/ Nationally acclaimed and known for perfectly cooked steaks and seafood. Progressive wine list features 100 wines by the glass. Wonderful private room which seats up to 75 persons. 7 min. by car from hotel.

SPENCER'S FOR STEAKS AND CHOPS	-Spencer's: http://www.spencersforsteaksandchops.com Traditional steakhouse. Great atmosphere and excellent wine list. Nice private room. 5 min. by car from hotel.
BAMBARA	-Bambara: http://www.bambara-slc.com A bustling bistro serving "New American" cuisine. Eclectic design, whimsical décor. Beautiful private room that can accommodate up to 24 persons 10 min. walk from hotel.
CUCINA GT TOSCANA	-Cucina Toscana: http://www.cucina-toscana.com/ Voted "Best Italian restaurant" in Utah. Delightful experience accentuated by your host: Valter Nassi. Large private room. 7 min by car from hotel.
MARKET STREET GRILL	-Market Street Grill http://www.gastronomyinc.com/msg/index.html Market Street Grill has a well-deserved reputation as Salt Lake's finest seafood restaurant. 10 min. walk from hotel.
FRESCO ITALIAN CAFE	-Fresco Italian Cafe http://www.frescoitaliancafe.com Excellent Northern Italian cuisine. Patio garden dining during summer, cozy fireside dining in the winter. 15 min. by car from hotel.
Martine CAFE · TAPAS 	-Martine http://www.dininginutah.com/martine.htm Casual European dining with an eclectic menu. Famous for tapas and Mediterranean food. 15 min. walk from hotel
	-The Paris http://www.theparis.net/ The Paris offers New American cuisine inspired by Italian, French and Mediterranean food cultures, with an award winning wine list, in a classic bistro. 15 min. by car from hotel

	-La Caille: http://www.lacaille.com Exquisite French chateau with traditional European cuisine. Beautiful gardens. Unparallel ambience regardless of seasons. 25 mn drive towards the mountains.
	-Log Haven: http://www.log-haven.com Rustic log mansion set in Millcreek Canyon. Voted best for atmosphere, food and wine. 20 min. by car from the hotel.

The concierge staff will be happy to assist you with your dinner reservations and transportation. Grand America Hotel Concierge direct line 801-258-6703.

36 HOURS IN SALT LAKE CITY

[Reprinted from the New York Times, June 3, 2010]

There's a new party in Salt Lake City. Utah liquor laws were normalized last year for the first time since 1935, allowing patrons simply to walk into a bar and order a drink, as if they were in any other city. Add to that a budding film scene (a spillover effect from the nearby Sundance Film Festival), a fresh crop of indie galleries and boutiques, and an open-door stance toward refugees and immigrants, which has made the city more cosmopolitan. The city even passed an anti-discrimination law last year that protects lesbian, gay, bisexual and transgender residents - and with backing from the Mormon Church.

Friday, 4 p.m.
1) CREATIVE SOUVENIRS

With its relatively affordable rents and D.I.Y. ethos, Salt Lake City is a bastion of creativity. To survey the design scene, stop by Frosty Darling (177 East Broadway; 801-532-4790; frostydarling.com), a whimsical gift shop stocked with retro candy and handmade clothing, accessories, and housewares by the owner, Gentry Blackburn, and other Utah designers. Signed & Numbered (2100 East 2100 South; 801-596-2093; signed-numbered.com) specializes in limited-edition, hand-pulled art prints and concert posters, from $8 to $150. And at Salt Lake Citizen (210 East 400 South; 801-363-3619; facebook.com/SaltLakeCitizen), in the atrium of the Main Library building, you'll find street-inspired clothing and accessories from 40 city designers, including embroidered wide-leg jeans and jewelry made of laser-cut acrylic.

7 p.m.
2) UTAH FARMS

Chain restaurants used to dominate Salt Lake City's food scene, but today intimate spots are popping up, run by young chefs inspired by the bounty of local organic farmers and artisanal purveyors. Leading the pack is Pago (878 South 900 East; 801-532-0777; pagoslc.com), a bustling neighborhood joint housed in a squat 1910 brick building. The chef Mike Richey spotlights local organic products in dishes like bagna cauda wagyu bavette steak with heirloom fingerling potatoes and local arugula ($29) in a rustic candle-lit room that seats just 50. Another newcomer is Forage (370 East 900 South; 801-708-7834; foragerestaurant.com), which serves wildly creative dishes like vanilla-scented diver scallops paired with smoked beluga lentils. A three-course dinner is $45.

9 p.m.
3) OPEN CITY

Raise a glass to celebrate the repeal of liquor laws that required bars to operate as private clubs and collect membership fees. The Red Door (57 West 200 South; 801-363-6030; behindthereddoor.com) has dim lighting, a great martini list and kitschy revolution décor — yes, that's a Che Guevara mural on the wall. Squatters Pub Brewery (147 West Broadway; 801-363-2739; squatters.com) serves high-gravity beers from the award-winning brewmaster Jenny Talley, like the 6 percent alcohol India Pale Ale. And Club Jam (751 North 300 West; 801-891-1162; jamslc.com) is a friendly gay bar with a house party feel and impromptu barbecues on the back patio.

Saturday, 9 a.m.
4) BOTANICAL BLISS

The Red Butte Garden, nestled in the foothills above the University of Utah campus (300 Wakara Way; 801-585-0556; redbuttegarden.org), has a newly planted rose garden, 3.5 miles of walking trails and morning yoga in the fragrance garden. For a wake-up hike, ask the front desk for directions to the Living Room, a lookout point named for the flat orange rocks that resemble couches. Sit back and absorb the expansive views of the valley, mountains and the Great Salt Lake.

11 a.m.
5) NOT JUST TEMPLES

Chart your own architecture tour. The city's Main Library (210 East 400 South; 801-524-8200; www.slcpl.lib.ut.us), a curving glass structure built in 2003 by the architect Moshe Safdie, has fireplaces on every floor and a rooftop garden with views of the city and the Wasatch Mountains. For older buildings, wander the Marmalade Historic District, home to many original pioneer homes from the 19th century, or go on a walking tour with the Utah Heritage Foundation (801-533-0858; utahheritagefoundation.com).

1 p.m.
6) DIVERSE PALATE

Although recent census figures put the city's population at 75.3 percent white, there is a growing ethnic population of Latinos, Pacific Islanders (particularly Samoan and Tongan), and refugees from Tibet, Bosnia and Somalia. Taste their influence at places like Himalayan Kitchen (360 South State Street; 801-328-2077; himalayankitchen.com), a down-home dining room with turmeric-yellow walls and red tablecloth tables, where dishes include Nepali goat curry ($15.95) and Himalayan momos, steamed chicken dumplings served with sesame seed sauce ($10.95).

3 p.m.
7) GIMME SUGAR

The Sugarhouse district is known for its one-of-a-kind shops and pedestrian-friendly mini-neighborhoods that are near the intersections of 900 East and 900 South (which locals call "9th and 9th"), and 1500 East and 1500 South ("15th and 15th"). Highlights include the Tea Grotto (2030 South 900 East; 801-466-8255; teagrotto.com), a funky teahouse that specializes in fair-trade and loose-leaf teas, and the charming King's English Bookshop (1511 South 1500 East; 801-484-9100; kingsenglish.com), a creaky old house filled with books and cozy reading nooks.

7 p.m.
8) ITALIAN HOUR

Salt Lake City has plenty of appealing Italian restaurants — Cucina Toscana and Lugäno are perpetual favorites — but the most romantic is arguably Fresco Italian Cafe (1513 South 1500 East; 801-486-1300; frescoitaliancafe.com), an intimate 14-table restaurant tucked off the main drag in a 1920s cottage. The menu is small but spot-on, with simple northern Italian dishes with a twist. The butternut squash ravioli, for example, is served with a splash of reduced apple cider and micro-planed hazelnuts ($18). There's a roaring fire, candlelight and, in the summer, dining on the brick patio.

9 p.m.
9) LIVE FROM UTAH

As the only sizable city between Denver and Northern California, Salt Lake City gets many touring bands passing through. Hear established and up-and-coming acts at places like the Urban Lounge (241 South 500 East; 801-746-0557; theurbanloungeslc.com) and Kilby Court (741 South Kilby Court; 801-364-3538; kilbycourt.com). If you want to make your own sweet music, stop by Keys on Main (242 South Main Street; 801-363-3638; keysonmain.com), a piano bar where the audience sings along.

Sunday, 10 a.m.
10) SECULAR MISSION

Mormons get around, and not just for missionary work. Latter-day Saint Humanitarian Center (1665 South Bennett Road; 801-240-5954; lds.org/placestovisit) is a humanitarian juggernaut that sends out handmade quilts, secondhand clothing and educational and medical supplies from their gigantic, factory-like complex to needy places around the world. If you're curious to see how it all works, take a 45-minute tour of the sprawling warehouse, where workers and volunteers sort the more than 100,000 pieces of clothing that arrive at the center daily. If you're inspired to help, you can stay after the tour and help prepare the humanitarian kits that regularly ship out to Haiti, Zimbabwe and other countries in crisis.

2 p.m.
11) OLYMPIC GHOSTS

Thrill-seekers head 28 miles east to Park City's Utah Olympic Park (3419 Olympic Parkway, Park City; 435-658-4200; olyparks.com), which hosted 14 medal events during the 2002 Winter Olympic Games. Even in the summer you can make like a medalist and fly down a slope at 70 miles per hour on a Comet bobsled, race along a slick steel alpine slide, or recreate a ski jump that is billed as the world's steepest zipline. Burgeoning culture and culinary sophistication has its benefits, but for sheer thrill, nothing beats an adrenaline rush.

SESSION 1—ROCK CHARACTERIZATION I: FRACTURE MECHANICS–EXPERIMENTAL

ARMA 10-369

An Experimental Study of Crack Coalescence in Pre-Cracked Specimens under Uniaxial Compression

Lee, H. and Jeon, S.
Department of Energy Resources Engineering, Seoul National University, Seoul, Korea

ABSTRACT
This study presents crack initiation, propagation and coalescence at or near pre-existing open cracks in prismatic Diastone (types of molded gypsum) and Hwangdeung granite specimens under uniaxial compression. The uniaxial compression tests were carried out for both single and double-flawed specimens in this study. The flaw geometry in the double-flawed specimen was a combination of a horizontal flaw and an underneath inclined flaw. Tensile and shear cracks were observed at the tip of the flaws for each material and the different cracking process depending on the material types were obtained. Crack coalescence types were varied according to the flaw geometry, i.e. the flaw inclination angle of the inclined flaw and were classified by the crack coalescence types of parallel flaws for overlapping flaw geometry in the previous studies. In addition, crack initiation and coalescence stresses were analyzed. From these experimental results, a better understanding of the crack characteristics and crack coalescence could be achieved.

ARMA 10-286

Crack Growth and Coalescence Mechanism in Granite Material Containing Two Surface Flaws under Uniaxial Compression

Yin P. Wong R.H. C. Chau K.T.
Civil and Structural Engineering Dept. of The Hong Kong Polytechnic University, Hong Kong, China

ABSTRACT
The main purpose of this study is to investigate the crack growth process and the coalescence mechanisms of two parallel pre-existing 3-D surface flaws under uniaxial compression in real rocks. In this study, the flaw angle, flaw length and the distance between two surface flaws (bridge length) are fixed. The bridge angle (the relative inclination between two flaws) is varied from 45° to 90°. Two observation systems (CCD camera and acoustic emission (AE) system) were used to study the propagation of cracks in the specimen. It was observed that petal cracks initiated along the interior surface of the flaw front. The propagation of the petal cracks is in three-dimensional curve shape towards to the surface of the specimen and extended to the bridge area. The coalescence mechanism depends on the bridge angle and bridge length. When the bridge angle is 90° with the bridge length equal to the flaw length, coalescence occurred. The coalescence crack is formed by the mixed mode of tensile cracks and petal cracks. But when the bridge angle is 45° with the same bridge length, no coalescence occurred. Further experimental study is required for coalescence mechanism of variables not fully investigated in the current study.

ARMA 10-374

Influence of 3D Internal Crack Spacing on Strength and Crack Propagation Pattern in Rock Sample Subjected to Tensile Stress

Yang, L.
Faculty of Engineering, Nagasaki University, Nagasaki 852-8521, Japan
Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China

Jiang, Y. and Li, B.
Faculty of Engineering, Nagasaki University, Nagasaki 852-8521, Japan

Li, S. and Li, M.
Geotechnical and Structural Engineering Research Center, Shandong University, Jinan 250061, China

ABSTRACT

The combined propagation and interaction of pre-existing cracks are important factors for rock mass overall instability and failure. Many experiments have been conducted to investigate the influence of 3D internal crack on strength and crack propagation pattern in rock samples. However, several issues like the influence of cracking spacing on the cracking pattern of rock subjected to tensile stress remain unsolved. In this study, a new type of rock-like material and a novel direct tensile apparatus are developed. Uniaxial tensile experiments on artificial rock samples containing two internal elliptical cracks with different crack spacing are conducted. Experimental results indicate that the tensile stress-strain curves of different samples exhibit 4-stage behaviors. Crack spacing has obvious influence on the tensile peak strength (σP) of sample. σP decreases gradually with the increase of crack spacing when $0<d/2a\leq1$ (where d represents crack spacing, and 2a is the length of crack), but increases as crack spacing increases when $1<d/2a\leq1.25$. Under tensile stress, wrapping wing crack and secondary crack initiate sequentially near the front of long axis of each pre-existing crack, and the lateral growth initiates near the front of short axis.

ARMA 10-237

Deviation from Linear Elastic Fracture in Near-Surface Hydraulic Fracturing Experiments with Rock

Makhnenko, R.Y.
University of Minnesota, Minneapolis, MN, USA

Bunger, A.P.
CSIRO Earth Science and Resource Engineering, Clayton, Victoria, Australia

Detournay, E.
University of Minnesota, Minneapolis, MN, USA

ABSTRACT

This paper presents the results of near-surface hydraulic fracturing experiments in a medium-grained gabbro that make use of different specimen sizes in order to observe the influence of rock heterogeneity and/or non LEFM behavior on fracture propagation. A comparison of the results with laboratory experiments in brittle elastic materials shows that fracture paths in rock usually do not monotonically approach the free surface. Moreover, they exhibit a high degree of non-symmetry, in contrast to experiments in glass or PMMA. An attempt to correlate crack path variation among different sized specimens to a size dependent fracture toughness has been initially inconclusive due to the noise caused by these crack path complexities. Nonetheless, these results provide an initial demonstration of non-LEFM behavior in hydraulic fracturing with implications for ongoing experiments aimed at quantifying the size effect on rock fracture toughness.

ARMA 10-360

Observation and Modeling of Hydraulic Fracture Initiation in Cohesionless Sand

Jasarevic, H., Golovin, E., Chudnovsky, A.
University of Illinois, Chicago, Illinois, U.S.A.

Dudley, J.W.
Shell Canada Limited, Calgary, Alberta, Canada

Wong, G.K.
Shell Exploration and Production Company, Houston, Texas, USA

ABSTRACT

This paper presents observations of hydraulically-driven fracture initiation (FI) in a cohesionless sand, and develops a Statistical Fracture Mechanics based model to predict the probability of initiating a fracture of a given length and orientation. The FI experiments are done in compacted 2-foot cubic sand packs in a stiff chamber under controlled anisotropic confining stresses. An aluminum pipe (9-mm ID) with 2-mm diameter perforations is used as a wellbore. A preheated low viscosity gel solution containing filter cake building solids is employed as a fracturing fluid, and injection rates are varied over two orders of magnitude. Post-test crosslinking of the gel results in solidification of the invaded zone (IZ), preserving the created fracture morphology and allowing excavation and cross sectioning for detailed analysis. Sectioning of the IZ near-wellbore region reveals a number of primary fractures initiated prior to formation of two main cracks. Tests stopped immediately after break down pressure indicate the number and locations of primary cracks are random and uncorrelated with fracturing fluid solids concentration. However, the lengths tend to follow the magnitude of hoop stress, and the average length decreases inversely proportional to cube root of the injection rate. Based on the stochastic nature of the FI a probabilistic model of HF initiation is formulated which predicts the probability distribution of primary initiation cracks formed around the wellbore as a function of hoop stress using one adjustable parameter. The prediction is in a reasonable agreement with the experimental observations.

SESSION 2—FIELD CASES, CAVERNS (CIVIL)

ARMA 10-401

Rock Mass Analysis and Support Measures for the No Business Creek Tunnel Project, Gwinnett County, Georgia (A Case Study)

Ashley Heckman, Project Tunnel Engineer
Lachel & Associates, Decatur, GA, USA

Jim Brady, P.E., Senior Tunnel Engineer
Lachel & Associates, Decatur, GA, USA

ABSTRACT

No Business Creek Tunnel Project located in Gwinnett County, Georgia is a 12 foot diameter TBM tunnel which extends 16,000 ft through the Piedmont Provence. The general geology consists mostly of metamorphic and igneous rocks. The anticipated rock mass conditions anticipated were hard, intact rock with Q-values greater than 10 for 80% of the tunnel length, blocky and seamy rock with Q-values from 1 to 10 for 15% of the excavated length and 5% was expected to be saprolite having a Q-value of less than 1. The corresponding support types prescribed for these anticipated ground conditions included a Type 1-two bolt pattern for the Q-values above 10, a Type 2-four bolt pattern for the Q-values between 1 and 10, and a Type 3-steel ribs and lagging as well as a 12 inch concrete liner for the Q-values less than 1. The ongoing mapping effort documented faults, shear zones, caverns, biotite seams, saprolite zones and discontinuity combinations that when paired with the inflow of groundwater, created initial support challenges that did not fall easily into the originally prescribed categories and had to be analyzed based on their individual characteristics. This paper describes the ground conditions, the analyses, as well as the initial ground support recommendations and measures for the excavated tunnel.

ARMA 10-386

Thoughts on Fault Zone Characterization for Tunneling

Richards, D. P.
Parsons Brinckerhoff, Denver, CO, USA

Williams, A.P.
Parsons Brinckerhoff, Los Angeles, CA, USA

Perry, D.L.
MACTEC Engineering, Los Angeles, CA, USA

ABSTRACT

Tunneling in fault zones almost always presents unusual, and sometimes excessive, challenges to the tunnel designer and the tunnel contractor. Appropriate characterization of fault zones during the design phase should provide a complete geotechnical characterization. However, tunnel depth, difficult topography, limited access, and meager budgets often preclude the possibility to characterize fault zone as completely as would be desired by the geotechnical engineer or engineering geologist. Proper characterization of fault zones must consider not only the geological factors and the geotechnical and hydro-geological conditions, but also the excavation and ground support methods and the size of the excavation. This paper examines some of the common methods of characterizing fault zones for tunneling such as Terzaghi, Heuer, GSI, Q, Riedmüller, and others, as well as some related characterization methods such as bimrock. It reviews the pros and cons of these characterization methods, and makes recommendations on their application for preparation of Geotechnical Baseline Reports in contract documents for the tunnelling industry. It also presents a comparison of pre-and post-construction fault zone characterizations in the Los Angeles Metro Red Line tunnel as it passed through the Hollywood Fault.

ARMA 10-346

Design and Construction of the Lake Tap Tunnel At Lake Dorothy Hydro, Juneau, Alaska

Brandon, S.H., Renegar, M.L. & Rohrbach, M.A.
Lachel & Associates, Dunn Loring, Virginia, USA

ABSTRACT

The Lake Dorothy Hydro project is located along the east bank of the Taku Inlet approximately 25.7 kilometers (16 miles) southeast of Juneau, Alaska. The project is owned and developed by Alaska Electric Light & Power which serves the greater Juneau area. One of the main components of the project is an approximate 264 meter (865 feet) long lake tap tunnel which was driven into the west side of Lake Dorothy. Lake taps are very specialized structures and adding to the challenge of the project was that the tunnel site was only accessible by helicopter due to the rugged terrain and remote mountaintop location of Lake Dorothy. This paper summarizes the design, construction methods, equipment utilized and logistics of tunnel construction in rugged, hard rock, glacial geology.

ARMA 10-364

Geological and Geomechanical Modeling Procedures Suitable for Civil, Mining and Petroleum Engineering

Marchesi, V. R.
GTEP/PUC-Rio, Rio de Janeiro, Rio de Janeiro, Brazil

Fontoura, S. A. B. da
Department of Civil Engineering, PUC-Rio, Rio de Janeiro, Rio de Janeiro, Brazil

ABSTRACT
A good knowledge of subsurface distribution of rock properties and its associated uncertainties is very useful for developing satisfactory geo-engineering projects. Traditional geotechnical engineering works are usually based on the so-called geotechnical cross-sections of the sub strata but recently, some efforts have been made to replace this practice with the usage of 3D subsurface property modeling in geotechnical studies. The oil-and-gas and mining industries, on the other hand, have been using for some time, in their daily operations, very sophisticated 3D modeling techniques to predict subsurface property distribution and its associated uncertainties. The aim of this paper is to describe the steps to be followed in order to construct a comprehensive model of the subsurface. Initially a brief review of the main elements of 3D geological and geomechanical modeling is presented, followed by a discussion of the main areas and tools available for application to rock engineering. Two case histories are presented in order to illustrate the proposed workflow. The first case history describes the evaluation of subsurface conditions for the purpose of an excavation, in a metamorphic environment, for a powerhouse and the second one describes the use of data from 42 oil wells to generate a model of a sedimentary environment for the purpose of planning further drilling in this area.

ARMA 10-411

Rock Engineering Assessments for Dam Stability Studies – Examples from New Zealand

Read, S. A. L.
GNS Science, Lower Hutt, New Zealand

Richards, L.
Rock Engineering Consultant, Canterbury, New Zealand

ABSTRACT
A detailed understanding of geological conditions is required to define realistic failure mechanisms and derive the required inputs for dam stability assessments. This paper initially outlines the rock material and rock mass properties at five New Zealand dam sites and then summarises approaches to the selection of design input parameters and analytical stability methods. The dams are founded on rock mass types that include closely-jointed greywacke, foliated schist and jointed sintered to moderately welded ignimbrite. Rock mass characterisation and laboratory strength testing provide inputs for classification systems such as the Geological Strength Index and failure criteria such as that of Hoek-Brown, but even where these are well defined, care is needed in the recognition of appropriate failure modes in the foundation geological model. The case histories include examples of the use of the Hoek-Brown failure criterion for estimating global rock mass strength, the Barton empirical equation for discontinuity shear strength and the empirical estimation of rock mass deformability. Analytical methods include both limit equilibrium and finite element methods and use of Strength Reduction Factor for sliding stability. A critical prior requirement for analyses is to assess whether they are for global rock mass strengths or structurally-defined kinematic mechanisms. The discussion section considers influences on input parameter values such as the Hoek Brown material constant mi.

SESSION 3 — PETROLEUM RESERVOIR GEOMECHANICS I

ARMA 10-359

Observation and Characterization of Hydraulic Fracture in Cohesionless Sand

Golovin, E., Jasarevic, H., Chudnovsky, A.
University of Illinois, Chicago, Illinois, U.S.A.

Dudley, J.W.
Shell Canada Limited, Calgary, Alberta, Canada

Wong, G.K.
Shell Exploration and Production Company, Houston, Texas, USA

ABSTRACT
Observations and characterization of laboratory scale hydraulic fracture (HF) in cohesionless sand are reported. The sand is compacted in a stiff rectangular (2'x2'x2') pressure chamber and subjected to controlled confining stresses px, py and pz. A heated low viscosity gel is employed as a fracturing fluid with variable concentration of filter-cake building solids, which solidifies after injection to preserve the fracture and invaded zone (IZ) morphology. The effect of injection rate, solids concentration and confining stress magnitude and anisotropy on the created HF is reported. Results show that depending on the value of these parameters the outcome spans across matrix flooding, cavity formation, single fracture formation or multiple branching stochastic fracturing. In many cases a fracture (displacement discontinuity) with a clearly defined boundary surrounded by a diffuse filtercake Is created. Increasing the injection rate or lowering the filter-cake building solids concentration can have similar effects. Both cases cause a transition from a roughly planer fracture to a more chaotic or diffuse fracture network and possible cavity formation. Increasing the confining stress magnitude and anisotropy also increases the confinement of the fracture and its' associated IZ to the plane perpendicular to the minimum principal stress. The presented results together with complementary data reported in the open literature present a consistent picture of cohesionless sand response to injection of various composition fluids with variable rate.

ARMA 10-202

Finite-Element Analysis of Deliberately Increasing the Wellbore Fracture Gradient

Salehi, S.
Missouri University of Science and Technology, Rolla, Missouri, USA

Nygaard, R.
Missouri University of Science and Technology, Rolla, Missouri, USA.

ABSTRACT
Lost circulation caused by low fracture gradients is the cause of many drilling related problems. When lost circulation occurs standard practice is to add lost circulation materials to stop mud to flowing into formations. To improve the treatment for lost circulation caused by low fracture gradients, special design materials are added to the mud to seal the induced fractures around the well bore. This operation is in the literature referred to as well bore strengthening. The size, type and geometry of sealing materials used in this process are the object of debate depending on the specific technique applied. Further, the physical mechanism of these techniques, in various rock permeability, is not fully understood. The main objective was to build a finite-element model for fracture growth, and a parametric study was conducted to determine the permeability effect on fracture growth and geometry. The results show that fracture growth is a strong function of material permeability therefore in highly permeable rocks, cracks widen more than they do ion less permeable rocks. The simulation results formed the basis of a fracture geometry model that permits prediction of a fracture geometry formed around the wellbore. The simulations also demonstrated that to enhance the sealing mechanism the fracture geometry formed in the formations is a contributing factor.

ARMA 10-338

Homogenized Models of Stress-Sensitive Tight Sand Rocks

Jeannin, L.
GDFSUEZ, Direction exploration-production, France

Dormieux, L.
ENPC, Institut Navier, France

ABSTRACT
This paper deals with the modeling of petrophysical properties under loadings of tight sand rocks. We use a micro-macro approach and describe the rock as an assemblage of impermeable grains surrounded by permeable interfaces and pores. The macroscopic permeability is estimated from a self-consistent homogenization scheme, considering Darcy's law in interfaces and pores. Then a mechanical constitutive description is associated to the fluid flow model. The macroscopic stress dependent permeability is estimated and compared with experimental results under loadings. Finally multiphase properties of tight sandstones are discussed in the framework of this model.

ARMA 10-350

Effect of Shale Bedding Plane Failure on Wellbore Stability – Example from Analyzing Stuck-Pipe Wells

Wu, B.
Schlumberger Data and Consulting Services, Beijing, China; now with CSIRO Earth Science and Resources Engineering, Melbourne, Australia

Tan, C. P.
Schlumberger Deepwater Technology Hub, Kuala Lumpur, Malaysia

ABSTRACT
Field A in Bohai Bay, China, was developed with high angle and horizontal wells. The development drilling had been hindered by severe stuck-pipe problems experienced in several wells in a short period. Drilling experience showed that the main problem was from the shale formation that directly overlies the reservoir. The high angle wells interacted with bedding planes of the shale resulting in large shale cavings and eventually hole collapse. Mechanical property of the shale was evaluated in laboratory using an ultrasonic method and scratch tests on large shale cavings recovered from the stuck-pipe wells. The tests were conducted in different orientations to the bedding planes. It was found that the strength along the bedding planes of the shale was much weaker than the intact shale material. Effect of bedding plane failure on wellbore stability in the shale was assessed using a transversely isotropic poroelastic and single plane of weakness model. The results showed that the bedding planes of the shale mainly affect high angle and horizontal wells (greater than 60 degrees inclination) drilled close to the minimum horizontal stress direction.

ARMA 10-198

Criterion for Fractures Crossing Frictional Interfaces at Non-orthogonal Angles

Gu, H. and Weng, X.
Schlumberger, Sugar Land, Texas, U.S.A.

ABSTRACT
In this work, the Renshaw and Pollard criterion for orthogonal intersections is extended to a fracture crossing frictional interfaces at non-orthogonal angles. A similar approach as in Renshaw and Pollard is used, and the stress field near the fracture tip and the interface is analyzed. The extended criterion could not be expressed explicitly in a simple formula, but crossing or no-crossing can be determined from a procedure involving a quadratic equation that can be easily solved using a simple computer routine. The results of crossing at all possible angles, i.e., angles fall between 0 and 90°, are obtained and explained. The smaller the angle between the fracture and the interface is, the more difficultly crossing occurs. In other words, the fracture is more likely to turn and propagate along the interface than to cross it as the angle is less than 90°. The quantitative results of crossing and no-crossing are also expressed graphically as functions of stress ratio, coefficient of friction, and intersection angle. The criterion can be applied in general analysis of fracture network complexities and in numerical fracture network simulators.

SESSION 4 — SLOPES, HIGH WALLS, STABILIZATION

ARMA 10-486

Full-Scale 3D Slope Stability Analysis of Sarcheshmeh Mine West Wall

Mortazavi, A.
Department of Mining & Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran

Asadipour M., Eslami M., Atashpanjeh A., & Salajegheh P.
Sarcheshmeh Copper Mine, Kerman, Iran

ABSTRACT
This paper deals with the stability analysis of Sarcheshmeh mine west wall large slope. The current height of Sarcheshmeh west wall is 450m and in the future planning pit depth exceeds over 800 m. With regard to the high future west wall (840 m), a comprehensive stability analysis was conducted. A sophisticated 3D model of the west wall was constructed and a comprehensive numerical analysis was conducted. Both current and future west wall geometries were analyzed and compared. Modeling results are in agreement with field observations and predict instabilities for the mid-section of Sarcheshmeh west wall.

ARMA 10-334

Toward a Tool for Managing Uncertainty in Large Open Pit Modelling – Finite Element Analysis of Jointed Rock Masses

Hammah, R.E., Yacoub, T.E., Corkum, B. & Riahi, A.
Rocscience Inc., Toronto, ON, Canada

Curran, J.H.
University of Toronto & Lassonde Institute, Toronto, ON, Canada

ABSTRACT
This paper explores the application of the Finite Element Method (FEM) with discontinuity networks and Shear Strength Reduction (SSR) analysis to analyze and design large open pit slopes. It discusses the uncertainties in the input parameters for an FEM model of a blocky rock slope, and describes the attributes of the modelling tools needed for practical open pit analysis. The paper then shows how the FEM, through scenario and probabilistic analysis, can be used to design optimal pit slopes under uncertainty.

ARMA 10-311

Simulation of Rock Slope Failures with the Numerical Manifold Method

Ning, Y.J.[1], An, X.M.[1] and Ma, G.W.[2,1]
[1] School of Civil and Environmental Engineering, Nanyang Technological University, Singapore
[2] School of Civil and Resource Engineering, University of Western Australia, Perth, Australia

ABSTRACT
In this paper, the numerical manifold method has been extended to simulate the practical rock slope failure process. The Mohr-Coulomb criterion with a tensile cutoff is employed to predict the crack initiation and propagation. A cover-division strategy is adopted to realize the fracturing process. Compared with the traditionally adopted element-division strategy, the cover-division strategy can avoid the mesh dependency to some extent because of the non-local nature of the stress. Algorithms are implemented to treat the manifold elements, the physical covers and the loops during the fracturing process. The developed program has been calibrated through a Brazilian test, and then applied to simulate the progressive failure of rock slopes with non-persistent joints. Numerical results indicate that it is able to capture the fracturing in intact rock bridge and finally allow the kinematic release. The numerical manifold method enabling fracturing is promising for such problems and deserves to be further developed for more complex applications in the future.

ARMA 10-425

3D Hydro-Mechanical Simulation of Faulted Open Pit Slopes

Beck, D. A.
Beck Arndt Engineering Pty Ltd, Sydney, NSW, Australia

Fillery, B.
Beck Arndt Engineering Pty Ltd, Perth, WA, Australia

Reusch, F.
Beck Arndt Engineering Pty Ltd, Berlin, Germany

ABSTRACT

Movements, stress and damage within pit slopes are coupled to sub-surface hydrology, yet slope stability models sometimes assume that the mechanical behavior and pore water pressure are not coupled. It is often assumed that uncoupling hydrological and mechanical simulations simplifies the analysis and that the engineer's intuition and experience can be used to account for the effects. This paper describes numerical experiments undertaken to demonstrate that even for a straightforward situation, simplified hydro-mechanical assumptions introduce problems that are not easily accounted for.

ARMA 10-163

A Three-Dimensional Model for Rock Slopes Based on Micromechanics

Lorig, L. J., Cundall, P. A., Damjanac, B. and Emam, S.
Itasca Consulting Group, Inc., Minneapolis, Minnesota USA

ABSTRACT

Conventional design methods for rock slopes typically involve the use of continuum strength criteria for the rock mass. The term "rock mass" denotes a large volume of fractured rock in which yield of both intact material and discontinuities may occur for overall failure to take place. The difficulty in characterizing a rock mass arises from the impossibility of testing directly a large extent of rock. Thus, empirical methods often are used to estimate the parameters for the rock-mass strength criterion. Such approaches ignore many important aspects, such as size effect and the complex way in which localized failure may propagate in a jointed medium. Recently, a numerical approach called the synthetic rock mass (SRM) has been developed, based on the distinct element method. Greater efficiency can be realized for brittle rock if a "lattice", consisting of point masses connected by springs, replaces the balls and contacts of a typical DEM model. The lattice model still allows fracture, by breakage of springs, and joint slip by using a modified version of the SJM (smooth joint model). The formulation of a new 3D program, Slope Model, based on a lattice representation of brittle rock is described. The program accepts a general DFN (discrete fracture network) consisting of multiple joint segments that are overlaid on the lattice springs. Fluid flow throughout the jointing network also is modeled, with the resulting pressures being used to compute effective stresses (hence, failure conditions) on each joint element. The influence of deformation on fluid pressure also is accounted for explicitly. Thus, Slope Model can simulate the time evolution of the field of pressures and flows due to mining activities, and the resulting influence on stability. Some examples are presented of the use of Slope Model to determine the stability of large 3D rock slopes.

SESSION 5 — FIELD CASES, STABILITY, SUPPORT (UNDERGROUND AND SURFACE MINING)

ARMA 10-472

Simulations of Roof Collapse and Cave Development using a Hybrid Finite/Discrete Approach

Elmo, D., Roberts, D. and Rogers, S.
Golder Associates Ltd., Vancouver, British Columbia, Canada

Yanske, T.
The Doe Run Company, Viburnum, Missouri, USA

ABSTRACT
An integrated method for modeling discrete fracture in rock masses under tensile and compressive stress fields has been applied to the study of roof collapse and cave development. The approach is based on a hybrid continuum/discrete technique incorporating fracture mechanics principles to simulate caving process in a more realistic manner than one approach alone. To account for the variability of the natural fracture system, underground mapping data are integrated in a stochastic discrete fracture network model to provide a realistic representation of the mine fracture system, and subsequently fracture traces are exported to the geomechanical model. Roof collapse and cave development is modeled as a combination of brittle failure of the intact rock bridges and shear failure along existing discontinuities. Whereas the analysis has to date been limited to the 2D case, it is argued that the approach is capable of simulating complex mechanisms, and reasonably addresses the question whether relatively simple numerical models are appropriate to analyze a rock engineering problem from different perspectives.

ARMA 10-151

Impact of Longwall Mining on Highways

Gutiérrez, J.J., Vallejo, L.E. and Lin, J-S.*
Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

Painter, R.
Pennsylvania Department of Transportation, Uniontown, Pennsylvania, USA* Corresponding author, jslin@pitt,.edu

ABSTRACT
Longwall mining is a common underground coal extraction technique in Northern Appalachia. The coal extraction takes the form of large rectangular areas whose width and length can reach up to 450 m and 4000 m, respectively, and have a thickness of around 2.0 m; mining depths range from 180 m to 280 m. A number of longwall panels have been mined underneath interstate highway I-79 in southwestern Pennsylvania causing large subsidence that raises concern for traffic safety. The Pennsylvania Department of Transportation monitored the impact of mining on the highway and collected the data on which this study was based. Specifically, field data obtained from eight longwall panels included time series of surveying data collected as each mine advanced underneath the highway, and inclinometer data obtained at selected points where stability of embankment slopes was a concern. With the aid of a genetic algorithm, a three dimensional subsidence model was developed that described the data well. The model gives the spatial and temporal distribution of surface subsidence in terms of the depth of the extracted coal panel, the width of panels, the thickness of extraction, and the location relative to the face of an advancing panel.

ARMA 10-193

Geomechanical Numerical Modelling Workflow for Large Open Pits Applied to Retro-Analysis of the East Wall of Toquepala Mine

Carvalho, J. L. And Castro, L.A.M.
Golder Associates Ltd., Mississauga, Ontario, Canada

Elmo, D.
Golder Associates Ltd., Burnaby, British Columbia, Canada

ABSTRACT

The geomechanical design of open pits includes the formulation of an Engineering Geology Model, derivation of slope design criteria and stability analyses. For large open pit projects, numerical modeling has gained increasing usage for the slope stability analyses to enhance the geomechanical understanding of the rock mass behaviour and possible modes of rock mass failure in order to evaluate the proposed inter-ramp and overall slope angles for new pit designs and push-backs. Complex failure mechanisms can be investigated with numerical models, considering the true discontinuous, inhomogeneous and anisotropic nature of the rock mass. Such methods include the discrete block approach (UDEC© and 3DEC©), the discrete fracture network approach (DFN, FracMan©), and the hybrid finite/discrete element approach (ELFEN©). Numerical back-analysis of a series of failures of the east wall (Slide XV) of Toquepala mine located on the western slopes of Cordillera Occidental, the southern Andes of Peru, was carried out using both the UDEC© (Carvalho et al., 2002) and ELFEN©. The results of the back-analyses of slope movement, impacting some 450 m of face length and a height of about 335 m, suggested that while toppling initiated in the volcanic rocks in the upper part of the wall at an early stage due to the adverse structure, the main controlling factors were the elastic deformations in the Diorite and Pebble Breccia Dyke exposed in the lower portion of the wall, which exacerbated the toppling/ravelling action of the upper part of the wall.

ARMA 10-227

Estimating the Squeeze Potential for Long, Deep Tunnels beneath the Santa Ana Mountains of Southern California

Williams, A.S.
Kleinfelder, Irvine, CA, U.S.A

ABSTRACT

As part of the feasibility evaluation of the Irvine-Corona Expressway Tunnels (ICE), closed-form analytical solutions developed by Hoek were used to estimate the potential for the rock mass to squeeze during mining and tunnel construction along the proposed tunnel corridor. The results using Hoek's method were compared with an empirical method developed by Goel et al., which utilizes the Rock Mass Quality (Q). Both of these methods predict that the rock mass will exhibit squeezing; however, the Goel et al. method predicts that the rock mass will exhibit squeezing at tunnel depths beyond 180 m regardless of lithology, while results using Hoek's method predict a range of critical depths from 50 to 470 m depending on lithology.

ARMA 10-276

Use of Levels in Underground Research Laboratories for Earth Sciences and Geotechnical Studies

Wang, J. S. Y.
Lawrence Berkeley National Laboratory, Berkeley, California, U.S.A.

Laughton, C.
Fermi National Accelerator Laboratory, Batavia, Illinois, U.S.A.

ABSTRACT
Concepts for developing existing mine levels to support underground research laboratory facilities are described. Multiple levels are being considered for an integrated suite of experiments at the Deep Underground Science and Engineering Laboratory to be built within the footprint of the abandoned Homestake Mine. The use of raise bore excavation techniques is considered to connect the underground levels to the surface, both for the design of large cavern excavations, such as those required for the Long Baseline Neutrino Experiment, and for the CO2 injection experiments, such as those required for studying buoyant flows and phase transitions. International collaborations are being expanded with experimentalists at the Laboratoire Souterrain à Bas Bruit and other underground laboratories for coupled-processes and geophysical-imaging studies. The progress of these activities contributes to the development of additional collaboration and teamwork in underground sciences and geotechnical studies.

SESSION 6 — SALT GEOMECHANICS I: LABORATORY AND MODELING

ARMA 10-287

Benchmarking of Geomechanical Constitutive Models for Rock Salt

Hampel, A.
Consultant (AH), Mainz, Germany

Günther, R.M., Salzer, K. and Minkley, W.
Institute for Geomechanics GmbH (IfG), Leipzig, Germany

Pudewills, A.
Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Leuger, B., Zapf, D., Staudtmeister, K. and Rokahr, R.
Leibniz University Hannover (IUB), Hannover, Germany

Herchen, K., Wolters, R. and Lux, K.-H.
Clausthal University of Technology (TUC), Clausthal-Zellerfeld, Germany

Schulze, O., Heemann, U. and Hunsche, U.
Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany

ABSTRACT
In numerical simulations for the design and stability analysis of underground openings in rock salt, the geomechanical and hydraulic behavior of the host rock is described with constitutive models. In recent decades, various advanced models and procedures for the determination of salt-type specific parameter values and for the handling of numerical simulations have been developed. Between 2004 and 2010, six project partners have been funded by the German Federal Ministry of Education and Research in two joint projects in order to document, check and compare their constitutive models for rock salt. The results of specific benchmark calculations demonstrate that the models describe correctly the relevant deformation phenomena in rock salt under various influences, i.e. transient and steady-state creep, the evolution of dilatancy and damage, short-term failure and long-term creep failure, post-failure behavior and residual strength. This ensures a high reliability of simulation results e.g. in the assessment, proof and long-term prediction of integrity of the geological barrier around an underground repository for hazardous wastes, or in the stability analysis of gas and oil storage caverns. In this contribution, a brief description of the involved constitutive models, some results of the benchmark calculations, and the conclusions from the results are presented.

ARMA 10-180

Coupled Thermal-Mechanical Analyses of a Generic Salt Repository for High Level Waste

Stone, C.M., Holland, J.F., Bean J.E. and Arguello, J.G.
Sandia National Laboratories, Albuquerque, NM, USA

ABSTRACT

Recent investments in the Sandia SIERRA Mechanics code suite have supplied the basic building blocks for realizing a multi-physics capability for repository systems engineering. These pieces are being assembled under an existing Laboratory Directed Research and Development effort to demonstrate an adaptive multi-physics framework for addressing the disparate time and length scales associated with geomechanics problems such as waste storage and resource extraction. As a demonstration of the features of this developing technology, a three-dimensional coupled thermal-mechanical analysis of a generic salt repository for high-level waste was performed. Two different analysis domains and mesh discretizations were utilized; one for the thermal analysis and a different discretization for the geomechanics analysis. Field transfer operators in the SIERRA toolkit were used to pass interpolated nodal temperature and displacement data between the different domains. Some of the discriminating features of this highly nonlinear, thermal-mechanical analysis include the use of large strain, large deformation mechanics, the use of both thermal and mechanical contact surfaces and the use of continuously updated radiation view factor calculations for the deforming storage rooms. The results of the analyses will be used to contrast the repository response solutions obtained for both a multi-mechanism deformation model (MD) and a power law creep (PLC) model representation of the salt behavior.of the upper part of the wall.

ARMA 10-493

Salt Barrier Integrity during Gas Pressure Build-Up in a Radioactive Waste Repository – Implications From Lab and Field Investigations

Till Popp and Wolfgang Minkley
Institut für Gebirgsmechanik GmbH, Saxony, Germany

ABSTRACT

Salt formations ensure safe isolation of disposed waste due to their impermeability for gases and fluids. However, significant gas quantities may be generated in the long-term (e.g. due to anaerobic corrosion) resulting in a time dependent pressure build-up. If the gas pressure would exceed the primary formation pressure pneumatic fracturing may take place in the overlying salt barrier, described as gas-frac scenario. For an assessment of the provable impact of increasing gas pressures on the salt integrity comprehensive experimental investigations were performed in the laboratory and field scale. Results from long-term gas injection tests in boreholes (500m depth) convincingly demonstrate that, if the gas pressure build-up equalizes the critical stress state in the salt, a rapid permeation process (i.e. a gas threshold) will take place. This process depends not on the amplitude of σmin but on the difference between pGas and σmin. The relevant incident is the order of permeability increase during the gas threshold, because it extends significantly the range of tolerable pressure build up rates. Only if the enhanced gas transport capacity of the surrounding salt is exceeded a further increase of pressure becomes likely which could result in pneumatic fracturing at overpressures in the order of several MPa.

ARMA 10-403

Application of the Multi-Mechanism Deformation Model for Three-Dimensional Simulations of Salt Behavior for the Strategic Petroleum Reserve

Sobolik, S. R., Bean, J. E., and Ehgartner, B. L.
Sandia National Laboratories, Albuquerque, New Mexico

ABSTRACT
The U.S. Strategic Petroleum Reserve stores crude oil in 62 solution-mined caverns in salt domes located in Texas and Louisiana. Historically, three-dimensional geomechanical simulations of the behavior of the caverns have been performed using a power law creep model. Using this method, and calibrating the creep coefficient to field data such as cavern closure and surface subsidence, has produced varying degrees of agreement with observed phenomena. However, as new salt dome locations are considered for oil storage facilities, pre-construction geomechanical analyses are required that need site-specific parameters developed from laboratory data obtained from core samples. The multi mechanism deformation (M-D) model is a rigorous mathematical description of both transient and steady state creep phenomena. Recent enhancements to the numerical integration algorithm within the model have created a more numerically stable implementation of the M-D model. This report presents computational analyses to compare the results of predictions of the geomechanical behavior at the West Hackberry SPR site using both models. The recently-published results using the power law creep model produced excellent agreement with an extensive set of field data. The M-D model results show similar agreement using parameters developed directly from laboratory data. It is also used to predict the behavior for the construction and operation of oil storage caverns at a new site, to identify potential problems before a final cavern layout is designed.

ARMA 10-384

The Excavation Damaged Zone in Rock Salt: Outcome of the EC Project THERESA

Wieczorek, K., Förster, B., Rothfuchs, T., and Zhang, C.-L.
Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, Braunschweig, Niedersachsen, Germany

Olivella, S.
Centre International de Métodes Numèrics en Enginyeria (CIMNE), Barcelona, Catalunya, Spain

Heemann, U.
Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Niedersachsen, Germany

Lerch, C.
DBE TECHNOLOGY GmbH, Peine, Niedersachsen, Germany

Pudewills, A.
Forschungszentrum Karlsruhe (FZK) GmbH, Karlsruhe, Baden-Württemberg, Germany

Kamlot, P.
Institut für Gebirgsmechanik (IfG), Leipzig, Sachsen, Germany

Grupa, J.
Nuclear Research and consultancy Group (NRG), Petten, Netherlands

Herchen, K.
Technische Universität Clausthal (TUC), Clausthal-Zellerfeld, Niedersachsen, Germany

Spiers, C.J.
Universiteit Utrecht, Utrecht, Netherlands

ABSTRACT
Excavation Damaged Zones (EDZ) in rock salt evolve as a result of the mechanical response of the rock to the excavation of underground openings. In the region close to the opening the dilatancy boundary will be exceeded, leading to microfracturing and an associated increase of porosity and permeability of the salt rock. EDZ evolution is especially relevant when considering the effectiveness of sealing structures in a nuclear waste repository. The focus of the salt group in the European Community project THERESA has been on modeling of rock salt dilatancy and on recompaction or healing effects. Since

reliable data on these phenomena are scarce, laboratory experiments with different objectives were performed to produce data for model calibration. A benchmark simulation of a laboratory test case was defined and performed using the calibrated models. Finally, one of the models was used to predict EDZ evolution and recompaction around a sealed drift and the results were used as input for the analysis with the Total System Performance Analysis (TSPA) code module LOPOS. This paper presents selected results of the various steps taken in the project.

SESSION 7—ROCK CHARACTERIZATION II: IN-SITU CHARACTERIZATION

ARMA 10-266

In-Situ Shear Strength of Rock-Concrete Contact Surface at the Abutments of a Concrete Dam

Gharouni Nik, M.
Iran University of Science and Technology (IUST), Tehran, Iran

ABSTRACT
In double curvature concrete dams in which the pressure resulted from impounding is imposed to the abutments, choosing the dam site (from a rock mechanics point of view) and recognizing rock properties at the abutments are of paramount importance. One of the most important parameters which have to be considered is the shear strength of the contact surface between rocks and concrete in the abutments. In this paper that is resulted from a series of in-situ direct shear tests on six concrete blocks prepared on the rocks inside the excavated nearly same-leveled galleries at the left and right abutments, the shear strength parameters and peak and residual strengths of the contact surface of rock- concrete at different applied normal stresses have been measured and reported.

ARMA 10-165

Relationship between Physical, Chemical, and Mineralogical Properties and Cohesion of Questa Rock Pile Materials

Boakye , K.
Geotechnical Engineer, Knight Piésold and Co. Denver, CO, USA & Department of Mineral Engineering, New Mexico Tech, Socorro, NM, USA

Fakhimi , A.
Professor, Department of Mineral Engineering, New Mexico Tech, Socorro, NM USA and Department of Civil Engineering, University of Tarbiat Moderres, Tehran, Iran

McLemore , V. T.
Senior Economic Geologist , New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, NM, USA

ABSTRACT
A modified in-situ direct shear test apparatus consisting of 30 cm and 60 cm metal shear boxes was designed and used to determine cohesion and internal friction angle of the Questa Rock Piles and natural analog materials. The main difference between the in-situ shear box and the conventional laboratory one is that this in-situ shear box is constructed of a single box that confines the prepared soil block. The lower half of the soil block is made of the earth material underneath the shear plane that is a semi-infinite domain. Tests were performed on the materials close to the surface of the rock piles and natural analog materials using normal stresses between 10 to 100 kPa to simulate the overburden stresses. Results indicate that cohesion shows a slight negative correlation with water content and a slight positive correlation with matric suction. The mineralogy and chemistry of the rock-pile and analog materials have little or no correlation with cohesion, which suggests that no single mineral or chemical element affects cohesion within the rock-pile and analog materials. The evidence of cohesion in the Questa rock piles is due to the presence of clay pockets within the rock piles, jarosite, gypsum, Fe-oxide cementing minerals, and soluble efflorescent salts, matric suction and interlocking of grains.

ARMA 10-324

Numerical Algorithm for Constructing 3D Initial Stress Field Matching Field Measurements

Madyarov, A. I. and Savitski, A. A.
Shell Exploration and Production Company, Houston, Texas, USA

ABSTRACT
A numerical approach for calculating the 3D virgin stress distribution in a subsurface model is developed. A superposition principle and an inversion technique are used to calculate a consistent stress field that satisfies the available measurements as well as equilibrium and compatibility equations. An elastic unloading response of the rock is assumed and applicability of the method for non-linear rocks is discussed. The solution to the forward problem is obtained using the finite element method. The ill-posed inverse problem is solved by minimizing a least-squares functional and by using regularization. The convergence of the algorithm is demonstrated with a numerical example. The work has application in the field of petroleum geomechanics where large-scale subsurface modeling requires stress initialization. The main advantage of the presented algorithm is that a consistent three dimensional initial stress field that matches the available scarce stress data is constructed and can be used in the subsequent modeling.

ARMA 10-121

Interpretation of In-Situ Stress at Baihetan Project

Meng, G. T. and Zhu, H. C.
Itasca Consulting China Ltd., Wuhan City, Hubei Province, China

Wu, G. Y. and Shi, A. C.
HydroChina Huadong Engineering Corporation, Hangzhou City, Zhejiang Province, China

Cornet, F.H
Institut de Physique du Globe de Strasbourg France

ABSTRACT
The paper presents the interpretations of some 845 sets of Hydraulic Fracturing test data for Baihetan project site by using HF test traces, numerical modeling against geological background, and observed spalling occurrence. It has been found, in terms of the interpretation of HF trace orientations, in-situ stress varies from gravity-governing near surface to horizontallydominated in the cavern area, and hydrostatic in between. The 40-degree offset of major principal stress orientations between the two cavern areas is associated with a few aspects including the differences of fracture network and topography, in terms of numerical models. Spalling is lined to stress localization in the areas near large-shear zones.

ARMA 10-145

Comparison of Sonic Fast-Shear Azimuth and Breakout Directions as Stress Indicators and Implication for Stress Estimation

Romain Prioul and Haitao Sun
Schlumberger-Doll Research, Cambridge, MA, USA

ABSTRACT
We compare two stress models, ”subsidiary” and ”borehole,” as mechanisms responsible for, respectively, the sonic fast-shear azimuth (FSA) and breakout directions for arbitrary well orientations. We show that the sonic FSA coincides with the ”maximum subsidiary principal stress” as the dipole shear is unaffected by borehole stress concentrations, and is, therefore, directly related to the relative deviatoric stress tensor described by the orientation of ¾h and ellipsoid factor R. In contrast, the breakout orientation, controlled by borehole stresses, occurs at a location where the compressive principal stress in the borehole tangential plane is maximum. We show that, to a first-order approximation, the breakout directions are also related to the orientation of ¾h and R as for normally pressured to slightly overpressured conditions, the breakout orientation is not very sensitive to the borehole mud pressure. Results indicate that, for arbitrary well orientations, sonic FSA and breakout direction are not necessarily at 90± of each other. This analysis implies that the sonic FSA, from stress-induced origin, is theoretically a better measurement to estimate the relative deviatoric stress tensor, and FSA observations from wells with at least two different orientations can be used to estimate the orientation of ¾h and R. To a first-order approximation, the same can be done using breakout orientations. Hence, sonic FSAs and breakout directions are complementary measurements.

SESSION 8--DYNAMICS I: INDUCED SEISMICITY

ARMA 10-233

Fracturing of Dry Porous Rock by Fluid Injection

Stanchits, S.
GFZ German Research Centre for Geosciences, Telegrafenberg D423, D-14473 Potsdam, Germany

Mayr, S. and Shapiro S.
Free University, Malteserstrasse 74-100, Build.D, D-12249 Berlin, Germany

Dresen, G.
GFZ German Research Centre for Geosciences, Telegrafenberg D426, D-14473 Potsdam, Germany

ABSTRACT
We studied fracturing of rock samples induced by water injection in axial compression tests on cylindrical specimens of Flechtingen sandstone by means of advanced acoustic emission (AE) technique. Injection of water into stressed dry sandstone induced appearance and diffusion of AE cloud, and later increase of pore pressure led to shear fracture of the rock. Ultrasonic velocity measurements and direct measurements of injected volume confirmed close relation of the water front position with the tip of induced AE cloud. Propagation of induced AE parallel to bedding plane is faster than perpendicular to bedding and related to anisotropy of permeability. Initial increase of pore pressure shows significant increase of tensile type of AE events, while approaching failure both shear and pore collapse types of AE events became dominant. Microstructural analysis of fractured samples shows excellent agreement between location of AE hypocenters and the faults. Results of presented researches could be applied for the interpretation of field microseismic data registered during monitoring of borehole fluid injections, for example, used for stimulations in hydrocarbon or geothermal reservoirs.

ARMA 10-520

Stimulated Fractured Reservoir DFN Models Calibrated with Microseismic Source Mechanisms

Williams-Stroud, S. C. and Eisner, L.
MicroSeismic, Inc., Houston, TX, USA

ABSTRACT
Methods for constraining discrete fracture network (DFN) models have historically relied on two very different scales for data: large-scale sources from which attributes can be coarsely defined for volume elements of 1000s of cubic meters such as seismic data, or small-scale sources where attributes of individual fractures are measured on a meter scale such as wellbores. Populating reservoir models with wellbore data requires upscaling the measured parameters, and the use of the large scale data types is accompanied by assumptions that can have significant uncertainties. A source of data that fills the gap intermediate to the large and small scale fracture parameters is microseismic data. During reservoir stimulation or production, acquisition of microseismic data with a surface array of geophones laid out in multiple azimuths and offsets (e.g., a star-like pattern above the well, or shallowly buried geophones in a grid like pattern), provides a broad sampling of the focal sphere that can be used to invert microseismic events for the source mechanism. This paper presents examples of DFN models constrained with source mechanisms and the implications for reservoir modeling of these more-highly constrained fracture network models.

ARMA 10-274

Enhanced Imaging of Hydraulic Fracturing through Induced Seismicity

Pettitt, W.S., Reyes-Montes, J.M. and Andrews, J.
Applied Seismology Consultants Ltd., Shrewsbury, UK.

Young, R.P.
University of Toronto, Canada

ABSTRACT
Hydrofracture stimulations are widely used to optimize production volumes and extraction rates in petroleum reservoirs, enhanced geothermal systems and preconditioning operations in caving mines. Microseismic monitoring is now becoming a standard tool for evaluating the geometry and evolution of the fracture network induced during a given treatment, principally by source locating microseismic hypocenters and visualizing these with respect to the treatment volume and infrastructure. Real-time processing can provide feed-back of this information during the treatment operations if the processing algorithms are both efficient and accurate, which are highly dependent on complexities in the local monitoring conditions, that can create path and receiver effects often not considered in traditional processing, and on the formation fracture mechanics and hydrofracture treatment conditions that can cause adverse source and path effects acting to reduce signal-to-noise ratios of the recorded data. Enhanced Microseismic Imaging provides increased resolution, greater processing efficiency and meaningful interpretations of the induced fracture network by using more efficient algorithms to extract greater numbers of locations and by using seismic source parameters in advanced analyses. We illustrate how the fracture network can be imaged using these techniques and provide meaningful results that can be fed back to investigate and engineer the fracture structure induced by the hydraulic stimulation.

ARMA 10-406

Geometrical and Inhomogeneous Raypath Effects on the Characterization of Open-pit Seismicity

Trifu, C-I. and Shumila, V.
ESG Inc., Kingston, Ontario, Canada

ABSTRACT
Typical open-pit seismic monitoring applications attempt to assess the slip potential behind the rock face during a wall retreat. They employ sub-surface sensor arrays several hundreds of meters in size, localized within the respective wall, for which event locations can be obtained using a homogeneous wave velocity model. More recently, seismic technology is asked to provide a characterization of the seismicity associated with the entire pit. In case of a pit-wide seismic sensor array several kilometers wide, a reliable analysis requires that the mine geometry and the presence of geological strata be accounted for. The shortest 'visible' ray-path technique, originally employed in computer graphics, allows for the use of a homogeneous velocity model with appropriate corrections, thus widening the effective monitoring area and improving accuracy and reliability of event locations. The Fast Marching Method is proposed to resolve event locations using an arbitrary 3D velocity model derived based on the mine geometry and structural geology information. Interestingly, this technique provides a general framework to account for excavations or caves in locating seismicity occurred in underground mining applications.

ARMA 10-475

A Discrete Fracture Network Approach for Evaluation of Hydraulic Fracture Stimulation of Naturally Fractured Reservoirs

Dershowitz, W.S., Lim, D.H. & Doe, T.W.
Golder Associates, Redmond, WA, USA

Cottrell, M.G.
Golder Associates, Belfast, County Down, UK

ABSTRACT
This paper describes the development of a 3-dimensional Discrete Fracture Network (DFN) approach for simulation and evaluation of hydraulic fracturing in low permeability fractured rock in the FracMan® reservoir analysis tool. The approach is based on an empirical algorithm approximating the effect of natural fractures and in situ stress on hydraulic fracture propagation. The algorithm distributes frac-fluid between the propagating hydraulic fracture and pre-existing natural fractures to predict both the geometry of the hydraulic fracture, and the reactivation of the natural fracture network. The technique is demonstrated by comparison against ELFEN® geomechanical simulations, and ny comparison of simulated and observed microseismic responses.

SESSION 9—SALT GEOMECHANICS II: CASE STUDIES

ARMA 10-239

Geomechanics Applied to the Well Design through Salt Layers in Brazil: A History Of Success

Costa, A.M.; Poiate Jr, E.; Amaral, C.S.; Gonçalves, C.J.C and Falcão, J.L.
PETROBRAS Petróleo Brasileiro S.A., Rio de Janeiro, Rio de Janeiro, Brazil

Pereira, A.
Pontifical Catholic University of Rio de Janeiro, Rio de Janeiro, Rio de Janeiro, Brazil

ABSTRACT
A major challenge in drilling in the Pre-salt area, in Brazil, arises from the special structural salt behavior, when compared to other geomaterials, since it develops high creep strain rates under high levels of deviatoric stresses and temperatures. The salt or evaporitic rocks, formed by the sea water evaporation, have different chemical compositions. In the Pre-salt area the more important types are: halite, carnallite and tachyhydrite. The tachyhydrite, for the same state variables, deviatoric stress and temperature, develops creep strain rates up to one hundred times higher than halite. Many operational problems, such as stuck pipe and casing collapse, have been reported when intercalation of these rocks within a thick layer is found. The challenge of designing excavations near tachyhydrite, began with the development of an underground mine to extract sylvinite ore in Northeast Brazil. The research that began in the 70s, to enable the mining of this ore overlying this rock, triggered one of the largest R&D projects in rock mechanics, including computing modeling, laboratory and field tests. For the design of the pre-salt wells this previous experience was used and additional triaxial creep tests were performed using a new rock mechanics laboratory. Field tests and computer modeling improvement were used to overcome the challenge of the Pre-salt drilling. This article describes the lessons learned on the geomechanical salt behavior and its application in subsalt wells design. In addition, it is presented the developed methodology validation, through comparison between computing modeling results with measurements carried out in experimental panels, in the potash mine, and with measurements obtained in an experimental well drilled for the purpose of calibrating and optimizing directional drilling in salt layers. These parameters and methodology have been used to support the design of the wells drilled in the Pre-Salt giant oil fields in Brazil with very successful results.

ARMA 10-169

Controls on In-Situ Stresses around Salt Bodies

Sanz, P. F. and Dasari, G. R.
ExxonMobil Upstream Research Company, Houston, Texas, USA

ABSTRACT
Reliable estimation of in-situ stresses around salt bodies is critical for planning safe and economic drilling programs. A better understanding of in-situ stresses before drilling can be achieved using geomechanical models that account for the complex interaction between creeping salt and the surrounding sediments. The present day stresses around salt bodies are investigated with finite element models using appropriate constitutive models for salt and its surrounding sediments. Salt is modeled using a visco-elastic creep law which captures the relaxation of deviatoric stresses. The response of the surrounding materials is assumed to be rate-independent and is modeled using elasticity or with a Mohr-Coulomb elasto-plastic constitutive law. Several finite element models were developed to identify major factors that control in-situ stress. The models reveal that one of the major controls is the connectivity of the salt body to its source. It is shown that when the salt body is connected to its source, the density contrast between the salt and surrounding sediments is the most important controlling factor. The stresses in completely isolated salt bodies are mainly controlled by the far-field stresses, the salt pressure, and the relative depth and geometry of the salt body.

ARMA 10-236

Crushed Salt Reconsolidation at Elevated Temperatures

Clayton, D.J. and Lee, M.Y.
Sandia National Laboratories, Carlsbad, NM, USA

Holcomb, D.J. and Bronowski, D.R.
Sandia National Laboratories, Albuquerque, NM, USA

ABSTRACT

There is a long history of testing crushed salt as backfill for the Waste Isolation Pilot Plant program, but testing was typically done at 100°C or less. Future applications may involve backfilling crushed salt around heat-generating waste packages, where near-field temperatures could reach 250°C or hotter. A series of experiments were conducted to investigate the effects of hydrostatic stress on run-of-mine salt at temperatures up to 250°C and pressures to 20 MPa. The results of these tests were compared with analogous modeling results. By comparing the modeling results at elevated temperatures to the experimental results, the adequacy of the current crushed salt reconsolidation model was evaluated. The model and experimental results both show an increase in the reconsolidation rate with temperature. The current crushed salt model predicts the experimental results well at a temperature of 100°C and matches the overall trends, but over-predicts the temperature dependence of the reconsolidation. Further development of the deformation mechanism activation energies would lead to a better prediction of the temperature dependence by the crushed salt reconsolidation model.

ARMA 10-492

Final Disposal in Rock Salt - Geomechanical Assessment of the Barrier Integrity

Wolfgang Minkley and Till Popp
Institut für Gebirgsmechanik GmbH, 02479 Leipzig, Saxony, Germany

ABSTRACT

Salt formations are favoured for storage of radioactive waste due to their unique isolation capacity. Because their water content is extremely low only solid state behaviour predominates with grain boundary diffusion. From this follows impermeability of salt rocks under undisturbed conditions. Linked flow paths inside the salt barrier may be created only under deviatoric stresses (1) if the acting stresses exceed the dilatancy boundary (= dilatancy criterion) or (2) at increased fluid pressure conditions if the acting normal stresses at the grain boundaries are lowered (= minimum stress criterion). Implementation of this advantage, i.e. inherent tightness, in repository concepts of storage of radioactive waste in salt requires as a prerequisite that the barriers are dimensioned with a sufficient thickness in that way that an entire inclusion succeeds. For long term warrantee of this state it has to be ensured that in the geological salt barrier under all acting stresses, i.e. convergence- or thermo-mechanical-induced, neither the dilatancy criterion nor the minimum stress criterion is violated.

ARMA 10-212

Challenges Faced to Execute Hydraulic Fracturing in Brazilian Pre-Salt Wells.

Azevedo, C. T., Rosolen, M. A., Rocha, J. D. H., Neumann, L. F., Melo, R.C.L.
Petrobras, Rio de Janeiro, R.J, Brazil

ABSTRACT

Petrobras has found a major discovery Brazilian carbonates located right below an extensive layer of salt. This pre-salt reservoir spreads throughout the Santos, Campos and Espírito Santo Basins, along the coast of the states of Santa Catarina until Espírito Santo, in water depths of approximately 2200 m (7218 ft) and reaches depths up to 7000 m (22966 ft). Since it is a heterogeneous reservoir with permeabilities varying over more than four orders of magnitude, stimulation is required in order to maximize the productivity. The objective of this work is to present the challenges that the company is facing to execute hydraulic fractures in the so called Pre-Salt wells such as: multiple points of closure, high closure pressures, high propagation pressures, high net pressures, near wellbore tortuosities, pressure dependent leakoff and height recession, apart from the presence of the salt layer in the top of a heterogeneous and profound reservoir without stress contrast. To illustrate these challenges, two history cases are presented, both showing hydraulic fracture premature screenouts.

MONDAY FLOOR PRESENTATIONS

ARMA 10-007

Lab Test of Brittle Behavior of Marble Sampled at Great Depth of Jinping II Hydropower Project

Chu,W.J, Zhang,C.S and Li,L.Q
HydroChina Huadong Engineering Corporation, Hangzhou City, Zhejiang, China

Zhu,H.C
Itasca Consulting China Ltd., Wuhan, Hubei, China

ABSTRACT
The Jinping II hydropower project consists of four headrace tunnels, the length of each tunnel approximately is 16.7 km with running parallel to each other and crossing the Jinping Mountain. The four headrace tunnels are designated 1 to 4, respectively. Tunnel 1 and 3 are being excavated by Drill & Blast methods (Section Diameter 13m) and Tunnels 2 and 4 are being mainly constructed by TBM (Section Diameter 12.4m). The average overburden above each tunnel is 2000m, the maximum overburden is 2500m. The main rock along the tunnels is Triassic marble. Laboratory results from

ARMA 10-107

Laboratory Testing on Pierre Shale for CO2 Sequestration under Clayey Caprock

Xuejun Zhou, Zhengwen Zeng and Hong Liu
University of North Dakota, Grand Forks, ND, USA

ABSTRACT
Caprocks are essential to the safe sequestration of CO2. Clayey rocks (clays, claystones, shales, mudrocks, siltstones) represent a major constituent of sedimentary basin fill and act as potential flow barriers and seals for subsurface fluid transport. Thus the investigation of caprock is usually an understanding of clayey rocks. Preliminary tests were conducted on the Pierre Shale from North Dakota's Pembina Gorge. Test results indicate that shales have a much lower Young's modulus compared with many other types of rock, such as limestones. In a basin scale, one may deduce that the clayey layer will bear much more deformation than its neighboring formations under the same tectonic activity. Dry shale shows a much higher peak axial strength than oil-wet shale; however, their residual strengths are comparable, which may indicate that for shale, the Mohr-Coulomb failure envelope constructed based on the residual strength may be even more reliable. Shale strength may also be decreased by exposure to CO2. Dry shale is relatively stable under single phase flow, even with water, provided that the confining pressure is high. However, serious deterioration was observed on the sample under CO2 flow after water flow. Both steady state and transient methods were used to determinate the permeability of rock. The rock matrix's permeability is found in the order of 10nD. The permeability is sensitive to confining pressure, the presence of fractures and flow history. uniaxial compression tests performed on Jinping marble samples indicate that a number of stages in the progressive failure process of rock can be identified through the combined analysis of strain measurement and acoustic emission (AE) data. Testing focused on identifying the crack initiation stress threshold σci and crack damage stress thresholds σcd. Results from the testing showed that the properties of the acoustic events are markedly different before and after crack initiation. Testing results also showed that all of the marble samples are damaged during coring.

ARMA 10-112

A Theoretical Explanation for Splitting of Stressed Rock under Axial Unloading Condition

Fan, P.X. [1,2], Wang, M.Y.[2] and Li, W.P.[2]

[1] State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology, Xuzhou, Jiangsu, China

[2] Engineering Institute of Engineering Corps, PLA University of Science and Technology, Nanjing, Jiangsu, China

ABSTRACT
The splitting of stressed rock under overall pressure conditions is a common phenomenon that is not well explained theoretically up to date. In this paper, a new theoretical model is proposed with respects to the stress concentration of nonuniformities distributed in rocks. Differential equation of Maxwell type was established, taking the unloading duration, material homogeneity and external conditions into consideration. The analysis based on the present model showed that: 1) three factors, namely the unloading duration, the scale of nonuniformities and the initial hydraulic stress, have significant influence on the tension stress concentration; 2) the local tension stress increase in a nonlinear fashion as the unloading duration decrease; 3)there is a nonlinear relationship between the scale of nonuniformities and the maximum local tension stress, with shorter unloading duration tends to excite smaller nonuniformities; 4) the maximum tension stress is proportional to the initial hydraulic stress. Results from simulating the rock splitting process under axial unloading conditions were cited to verify the present model. As the model predicted, extension fracture could only be simulated in the abrupt mode, while samples with finer grain size and better sorting showed higher resistance to extension fracture.

ARMA 10-116

Analysis on Geological Factors Having Impact on Deformation of Surrounding Rock Masses of Large Cross-section Highway Tunnels

Hui-jun Yang, Jin-Ying Zhai, Hong-Yang Liu
China Railway Tunnel Group Co., Ltd., Luoyang 471009, Henan, China

ABSTRACT
New Qidaoliang tunnel is a highway tunnel that has the largest excavation cross-section in Gansu province of China. The tunnel is located in complex geological conditions. In the paper, analysis is made on the curves of the measured convergence of the surrounding rock masses of the tunnel and on the degree of the impact on the rock mass deformation imposed by such factors as rock mass quality, fault and fracture zones, spatial positions of discontinuity interfaces, ground water and tunnel cover depth. The following conclusions are drawn: (1) The rock mass quality is in inverse proportion to the deformation of the rock masses occurring after tunnel excavation; (2)The deformation of the surrounding rock masses in fault and fracture zones is huge and lasts longer time; (3) Where the tunnel driving direction is opposite to the dip of the strata and the dip angle is large, the deformation of the surrounding rock masses is small; (4) Ground water can result in reduction in rock mass stability and increase in rock mass deformation; (5) The cover of the tunnel is one of the factors that have impact on the deformation of the surrounding rock mass.
Key Words: tunnel; deformation; geological factor

ARMA 10-118

Design Support for Intersection of Underground Openings

Amusin Boris
NYC SCA, L.I.C., NY, USA

Eisenberg Julia
Caldwell College, New Jersey, USA

ABSTRACT
A design methodology is developed based on analysis of practical consequences for intersection/junction of underground openings. Mechanism of interaction support with rock mass is simulated based on theoretical solution. Empirical correction factors are introduced into geomechanical and technological initial data. The 3D problem for intersections is solved as a 2D problem by introducing an effective depth. The effective depth takes into account additional stress from the adjacent opening. Analysis of 3D numerical solutions for intersections and examples of calculation based on the proposed method are presented.

ARMA 10-119

Numerical Evaluation of Cavern Layout Design for the Baihetan Hydropower Project in China

Jiang, Y.L. and Xu, J.Q.
HydroChina Huadong Engineering Corporation, Hangzhou City, Zhejiang Province, China

Meng, G. T., Zhu, H.C., and Li, H.
Itasca Consulting China Ltd., Wuhan City, Hubei Province, China

Wang, Y. F.
China Three Gorges Corporation, Yichang City, Hubei Province, China

ABSTRACT
Two large caverns with span of 32.2m and height of about 80m each are planned to build inside both of river banks in Baihetan, China. Three types of challenging issues, stress-inducing brittle failure, large deformation, and block instability, are the concerns at current stage of feasibility study. Stability analysis with numerical modeling was thus conducted to examine each of these potential issues with various scenarios corresponding to each of the layout proposals, respectively. The modeling results predicted potential risks of failure, and provided reliable evidences for determining the favorable layout.

ARMA 10-126

Behavior of Marble at Jinping II Project—Part 1: Intact Rock

Shan, Z.G, Wu, X.M., Yan, P., and Liu, N.
HydroChina Huadong Engineering Corporation, Hangzhou, Zhejiang, China

Zhu, Y. S and Zhu, H.C.
Itasca Consulting China Ltd., Wuhan, Hubei, China

ABSTRACT
This paper introduces the studies of rock mechanics behaviors of marble for the Jinping II project. Fracturing can occur in marble under relative low stress level as pre-peak response to loading. As a result, drilling at great depth below a certain depth, such as 1000m from surface, can induce damage to the rock specimen taking from drilling cores. A damage-free sampling technique has been proposed and applied for solving this problem. Lab test indicates that marble presents a complex brittle-ductile-plastic transition behavior as post-peak responses to the increase of confinement. Such behavior can be numerically duplicated with Hoek-Brown constitutive law built in FLAC3D.

ARMA 10-137

Stability Analysis of Rock Slopes using Block Theory

Haswanto
Department of Mining, University of Trisakti, Jakarta, Indonesia. E-mail : haswanto_wa@yahoo.com. Ghani Rafek A. Department of Geology, UKM, Bangi, Malaysia. E-mail : aghani@ukm.my

ABSTRACT
The system of discontinuities that transverses a rock mass delimits rock blocks of many sizes, shapes and positions in a surficial excavation. By using the block theory, it is a possible to determine the most critical block within these isolated masses, which are denoted as key blocks and potential key blocks. This study is an example of the application of the block theory and kinematic analysis for a granite rock mass at a cut slope located at Fraser's Hill in Pahang, Malaysia. The purpose of this study is to indentify key blocks, potential key blocks, stable blocks and tapered blocks, and to determine the safety factor as well as the safe slope angle for this rock slope. Key-word : Block Theory, key blocks, kinematics, safety factor, stability analysis.

ARMA 10-160

A New Device for Measuring In-situ Stresses by Using Acoustic Emissions in Rocks

Fa, L.[1,2,] Zeng, Z.[1] and Liu, H.[1]
[1] Department of Geology & Geological Engineering, University of North Dakota, Grand Forks, North Dakota, USA

[2] School of Electronics Engineering, Xi'an Institute of Post and Telecommunications, Xi'an, Shaanxi, China

ABSTRACT
This paper introduces the development of a new device, Kaiser in-situ stress system. This device is designed to measure in-situ stresses via detected acoustic emissions caused by the Kaiser effect in rocks. With the assumption that the orientation of one of the three principal in-situ stresses is known, the magnitude and orientation of all the three principal in-situ stresses can then be calculated by using the Kaiser stresses measured from four specimens cut from four different orientations of one underground core. The method can be useful to rock engineering projects in which in-situ stresses play an important role. This device is designed to be portable and compatible to both desktop and laptop computers. By using a special data compression algorithm, the device can record not only the relationship between the acoustic emission event number and the exerted load on the rock specimen, but also the waveforms of the acoustic emission signals in time domain for the total measurement process. Therefore, the system provides a technical means for both the analysis of the acoustic emission signals in time and frequency domains and the economic and efficient evaluation of the three principal stresses in rocks. This can be useful to assess the in-situ stress field in oil and gas reservoirs.

ARMA 10-161

Equivalent Continuum Modeling For Wave Propagation In Jointed Rock Masses

Oleg Vorobiev and Tarabay Antoun
LLNL, Livermore, CA, USA

ABSTRACT
This study presents 2D and 3D simulations of nonlinear wave propagating through jointed rock masses. The simulations were performed using the Lagrangian hydrocode GEODYN-L with joints treated explicitly using an advanced contact algorithm. We studied both isotropic and anisotropic joint representations. For a uniformly and randomly jointed geologic medium, our results show that the properties of the joints can be combined with the properties of the intact rock to develop an equivalent continuum model suitable for analyzing wave propagation through the jointed medium.

ARMA 10-166

Study on High Speed Slide Mechanism of Qianjiangping Landslide in China Three Gorges Reservoir

Xiao, Shi-rong
China Three Gorges University Key Laboratory of Geological Hazards in Three Gorges Reservoir Area, Ministry of Education, Yichang 443002, China

ABSTRACT
The Qianjiangping landslide, located in China's Three Gorges Reservoir (TGR), occurred on 13th July 2003 , one month after the first impoundment to 135m a.s.l. of TGR water level. This is the first reservoir triggered landslide in TGR. This huge landslide was a high speed dip rockslide with a volume of 15 million m,a maximum sliding velocity of 16m/s. The maximum surge height was 24.5m,and the sliding process was finished in less then 1 minute. The catastrophic landslide caused 10 people died, 14 people disappeared, destroyed 129 houses and 4 factories , and left 1200 people homeless . After the landslide, the author continued research on the high speed slide mechanism in order to be able to predict the same kind of landslide disaster in the TGR area and elsewhere in the world. On the research effort on the high speed slide mechanism seen in the Qianjiangping landslide is based on geologic analysis and numerical computations, concluded that the Qianjiangping landslide had a typical geological structure needed to gestate a high speed landslide; the great decline in shear strength in the shear zone (from peak to residual) is the essential cause for the high initial sliding speed; and the potential energy of the high slope and the liquefaction of the shear zone accelerated the sliding.

ARMA 10-168

Research on the Mechanism of the Floor Heave Caused by Grouting Pressure and Its Numerical Simulation

Rentai Liu,Shucai Li, Qingsong Zhang, Weiwei Han, Xiao Zhang
Geotechnical and Structural Engineering Research Center, Shandong University, Shandong 250061, China

ABSTRACT
In the underground engineering construction, grouting is a common means of the disaster management projects. Grouting can improve the mechanical parameters of surrounding rock and the stress state of surrounding rock. Grouting is benefit for the surrounding rock stability and roadway safety in long term. But the slurry can not have the carrying capacity immediately; the pump pressure will be passed on the surrounding rock. The pump pressure is an additional load, and it is result in a large deformation of the soft rock roadway. Using the composite beam model, the critical value of the grouting pressure leading to floor heave is obtained. By numerical simulation method, the value of the grouting pressure carried by the surrounding rock is calculated. Through theoretical analysis and numerical simulation methods, the limit grouting pressure is determined in Longgu coal mine. By the observation of surrounding rock deformation in Longgu coal mine, the law of the rock deformation under grouting pressure is analyzed. This research is a good reference for similar projects.
KEY WORDS: grouting pressure; numerical simulation; floor heave; monitoring measurement.

ARMA 10-173

Deriving Rock Mechanical Properties using Resistivity Log Data

Santana, C. and Bai, M.
Halliburton, Houston, TX, USA

ABSTRACT
Sonic velocities from wireline/LWD logs have been used to establish relationships with rock mechanical properties. Because sonic logs frequently are not available, there has been great interest in relating rock mechanical properties and other logs (e.g., porosity logs). Resistivity logs, are commonly acquired logs. The relationship between sonic and resistivity logs is often masked by factors, such as fluid salinity and hydrocarbon saturation. The evidence indicates that filtering these factors out will increase the probability that the resistivity log would correlate well with the sonic log, and ultimately, with rock mechanical properties. This paper presents a methodology to minimize background noise from the resistivity log data and, moreover, to select and categorize the interest points in levels of rock strength. Overall, it involves establishing a baseline and offset lines in the resistivity log and the sonic log. These lines are compared quantitatively to the original log curves to identify and filter out data points associated with factors that perturb the trend between sonic slowness and resistivity. Techniques used to derive the resistivity baseline (curve smoothing techniques) and to provide the reasonable ranges for the factors that cause resistivity offsets (based on resistivity models from the literature) are presented in the paper. The proposed methodology is demonstrated using case studies from wells drilled in the Gulf of Mexico.

ARMA 10-184

A Safety Study of Transition Segments for A Branched Tunnel

Li-Yuan Yu And Shu-Cai Li
Research Center of Geotechnical and Structural Engineering, Shandong University, Jinan, Shandong, P.R. China

Ming-Bing Wang
School of Science, Shandong Jianzhu University, Jinan, Shandong, P.R. China

Guo-Fu Sun
School of Business Administration, Shandong University of Finance, Jinan, Shandong, P.R. China

ABSTRACT
In order to overcome the difficulties of the joint bridge-tunnel projects which commonly arise in highway engineering in the west of China, the branched tunnel as a new type of tunnel has been put suggested by designers. In the branched

tunnel, the transition segments between the large-span segment and the multi-arch segment, and also between the multi-arch segment and the neighboring segment, were the focal point and difficulty in the overall tunnel engineering effort. Numerical analysis and model testing were employed to simulate excavations for the two transition segments. Finite element modeling was applied. In addition, the a 3D geomechanics model was used as bench top testing was undertaken. Iron barite sand cementation material (IBSCM) was developed in the model test. Site monitoring measurement are also-provided. Based on numerical and physical modeling and monitoring, it was determined that the positions of vault, floor, interval wall and interval rock column are seriously affected by tunnel excavation; and that Transition Segment is more unstable than Transition Segment.

ARMA 10-187

Mechanical Properties, Flow Properties, and Heterogeneous CO2 Sorption in Confined Powder River Coal Cores

Jikich, S.A., McIntyre, D. and Bromhal, G.S.
National Energy Technology Laboratory, Morgantown, West Virginia, USA

Crandall, D.
URS/Washington Division, Morgantown, West Virginia, USA

ABSTRACT

Understanding the effects of carbon dioxide (CO2) sorption in coal is important to designing sequestration projects in unminable coal seams. Subsurface coals are affected by three-dimensional stresses, therefore, stress effects on mechanical and flow properties of coal must be evaluated. When CO2 flows and sorbs in coal, these properties will again be affected. In this work two sub-bituminous cores from the Powder River Basin were mechanically deformed using a three-dimensional hydrostatic coreholder. The permeability of the coal cores was measured during the coal deformation. CO2 sorption in these cores was then performed over a period of weeks. Computed Tomography (CT) scanning of the cores was conducted periodically over this period to measure the density changes due to sorption. CO2 sorption was measured at a constant effective stress. CT measurements of bulk density were then used to determine the elastic properties of the coal. The results show that the coal is very susceptible to external deformation, that mechanical and flow properties depend on the effective stress and the location within the core, and that CO2 sorption varies significantly throughout the core. The Langmuir equation was shown to fit well to the average sorption in the confined coal samples.

ARMA 10-201

Geomechanical Modeling of a Reservoir-Scale Fault-Related Fold: The Bargy Anticline, France

Smart, K.J., Ferrill, D.A., Morris, A.P., and McGinnis, R.N.
Dept. of Earth, Material, and Planetary Sciences, Southwest Research Institute®, San Antonio, TX, USA

ABSTRACT

The ability to predict rock mass deformation deep underground is important to a broad spectrum of endeavors including oil and gas exploration and production, geothermal reservoir characterization and management, and subsurface disposal of CO2. Geomechanical modeling can predict the onset of failure and the type and abundance of deformation features. The Bargy anticline in the northern Subalpine Chain of France is an oil-field-scale fault-related fold. Excellent exposure allows structural characterization at a range of scales. In this study, fold geometry and outcrop-scale faults and fractures provide calibration data for comparison to two-dimensional finite element models of the Bargy anticline. Initial model geometry is based on restorable geologic cross sections and incorporates the observed mechanical stratigraphy. An elastic-plastic constitutive relationship is used so that permanent strains can develop in response to the applied loads. Faults and bedding-slip surfaces are simulated with frictional sliding interfaces. Loading consists of gravity and an overburden pressure to simulate inferred burial depth, followed by a displacement boundary condition to simulate thrusting. The finite element modeling results show that overall fold geometry and strain distribution can be matched, and demonstrate that well-designed geomechanical modeling can be applied to fracture and subseismic fault prediction in geologic structures.

ARMA 10-211

Development of Borehole Jack Fracturing Technique for Crustal Stress Measurement

Yokoyama, T. and Ogawa, K.
OYO Corporation, Saitama, Japan

Sano, O.
The University of Tokyo, Tokyo, Japan

Hirata, A. and Mizuta, Y.
Sojo University, Kumamoto, Japan

ABSTRACT
In order to measure of crustal stresses at great depths more than 1000m from the ground surface, we have been promoting research and development of borehole jack fracturing technique. The theory of this technique is described by the relations between jack pressure and stress state around the borehole. Specifically, when a borehole wall is loaded by a borehole jack, a pair of axial new fractures will be open oppositely. After unloading, if the same place on the borehole wall is loaded by the jack, a pair of fractures is open again. Two principal stresses and azimuth directions of crustal stress in the plane perpendicular to the borehole axis are determined by the re-opening pressures and azimuth directions of the fractures respectively. The feature of this method is to induce a pair of axial fractures in any direction and measure a displacement of the fracture opening. Consequently, it is allowed us to determine the re-opening pressure with more precision. This paper describes the results of numerical analyses, laboratory experiments and field tests.

ARMA 10-216

Geomechanical Study for Stability and Land Protection Evaluation at a Large Quarry Site

Cravero, M. and Iabichino, G.
CNR - Istituto di Geologia Ambientale e Geoingegneria (IGAG – CNR), Torino, Italy

Lollino, G.
CNR - Istituto di Ricerca per la Protezione idrogeologica (IRPI – CNR), Torino, Italy

Piana, F.
CNR - Istituto di Geoscienze e Georisorse (IGG – CNR), Torino, Italy

ABSTRACT
The paper synthesizes the results of a study that was aimed at the rock engineering estimation of the present static condition of excavated rock slopes at a large limestone quarry site. The quarry site was divided into six lythostructural homogeneous sectors. On the basis of field geo-structural surveys, laboratory mechanical characterization of the rock and joints, rock mass classification procedures and kinematical analysis, including the block theory, a judgement has been made on the quality of the rock slope behaviour along the entire quarry face. A rockfall analysis has also been performed. In all the quarry sectors, the present geometry of the quarry rock slopes is prone to localized, cortical failures although with different intensities. This kind of evidence has been qualitatively verified using a idealized DEM model of the slope and of the blocky rock mass structure. The computation evaluations of the rock block trajectories have shown that blocks could reach the quarry plant area and, in spite of a protection embankment, could even reach the state road that runs along the side of the quarry. Definitive remediation, consisting of reexcavation to flatten the rock slopes, has been suggested to prevent the rockfall. This measure should remove the kinematical possibility of block instability and rockfall occurring.

ARMA 10-224

Estimating In Situ Stress Magnitudes and Orientations in an Albertan Field in Western Canada

Teichrob, R., Kustamsi, A., Hareland, G., and Odiegwu, U.
University of Calgary, Calgary, AB, Canada

ABSTRACT
This study describes efforts to use available well logs and fracturing treatment data to estimate in situ stress profiles and orientations in an Albertan Field in Western Canada. Two methods were used in estimating minimum horizontal stress magnitudes, i.e. computing from logs and from drilling data. For the log approach we compared uniaxial and plane strain stress models taking the values from typical log data to obtain the minimum horizontal stress versus depth. The drilling data were used to calculate the apparent rock strength and in conjunction with a normalized failure criterion and the coefficient for earth at rest the minimum horizontal stress was obtained. The minimum horizontal stress was compared to the fracture closure stress from fracture test in some of the formation zones. Vertical stress magnitudes were calculated by integrating bulk density logs from the surface to the depth of interest. Statistical analysis was performed on breakouts observed in image log to determine the horizontal stress directions. The stress profiles for the wells were prepared as input for hydraulic fracture treatment modeling in horizontal gas wells of the reservoir zones.

ARMA 10-226

CO2 Injection Evaluation in the Arbuckle Formation under Thrall-Aagard Reservoir in Kansas

Weon Shik Han, Si-Yong Lee, Chuan Lu, Brian J. McPherson
Energy and Geoscience Institute, Salt Lake City, Utah

Martin Dubois
Cap CO2, LLC

ABSTRACT
We used numerical simulation experiments to understand a potential CO2 injection site, the Arbuckle formation under the Thrall-Aagard reservoir in Kansas. Including the potential CO2 plume migration, convective mixing, and drying-out processes, we investigated thermophysical processes associated with CO2 injection, namely, Joule-Thompson cooling and enthalpy changes associated water vaporization and CO2 dissolution. Results suggest that the rate of pressure dissipation after stopping injection was rapid in the Arbuckle formation since this formation is hydrologically connected to open surface, the Ozark Plateau aquifer system in Missouri. Consequently, CO2 densities radically drop with pressure dissipation. In addition, as supercriticalphase CO2 comes into contact with formation brine, CO2 will dissolve into this fluid, an exothermic reaction at typical in situ conditions appropriate for CO2 sequestration. Thus, CO2 dissolution potentially increases both the enthalpy and temperature of CO2-laden brine. However, the magnitude of this increase was minor in most cases (less than 1°C). In summary, the detailed understanding of thermophysical properties of CO2 is necessary prior to field-scale deployment in this site.

ARMA 10-234

Hydraulic Fracture Optimization for High Deviated Wells in an Thin Turbidites Sandstone Formation in Soledad Field, Chicontepec Basin, Mexico

Rabe, C.
Geomechanics International, Perth, West Australia, Australia

Ortiz-Ramirez, J.
PEMEX, Poza Rica, Veracruz, Mexico

ABSTRACT
This paper presents a developed methodology integrating geomechanics, reservoir engineering and completion design to optimize the hydraulic fracture in horizontal wells in the Soledad Field, Chicontepec Basin. The impact of geomechanics model, fracture design as well as the fluid flow due to oil production was analyzed. Prediction of forecast oil production considering the impact of stress state and fracture shape and its propagation were considered in the technical and economical perspectives based on expected oil production. Impact of pore pressure to re-fracturing operations is also presented. In this paper we discuss the impact of geomechanics in the completion strategy to optimize production in the studied area.

ARMA 10-240

Feasibility Study of Underground Coal Gasification Combined with CO2 Capture and Sequestration in Williston Basin, North Dakota

Peng Pei, Zhengwen Zeng, and Jun He
Department of Geology and Geological Engineering, University of North Dakota, Grand Forks, ND, USA

ABSTRACT
Underground coal gasification (UCG) can exploit coal resources which are not economic to mine, and convert the coal resources into high rank energy with a sustainable, lower cost process and smaller land occupation. The UCG technology currently has received renascent interests as its ability to combine with carbon capture and sequestration (CCS), in which CO2 is separated from the produced syngas and injected into adjacent coal seams for enhanced coalbed methane recovery and CO2 sequestration. This paper presents the primary investigation to the feasibility of the UCG-CCS process in Williston Basin, North Dakota. Information and data about the Fort Union coals in North Dakota are collected and analyzed in terms of coal bed thickness, overburden thickness, lithology properties and other factors. Two areas of Harmon Coal zone in Golden Valley County and Slope County are selected as prospective sites for UCG and UCG-CCS application. Lithological models of these two coal zones are established respectively. Based on the models, the geometry of the coal beds, and compositions of the overburden are investigated for a better understanding of the specific coal zones. Possibilities of conducting UCG-CCS projects in the two coal zones are discussed and plans for future works are suggested.

ARMA 10-252

Finite Volume Numerical Analysis of Rock Joint Geometry Effect on the Penetration Length of Grout under the Transient Flow

Khani, J., Sharifzadeh, M. and Shahriar, K.
Mining & Metallurgy Engineering Faculty, Amirkabir University of Technology, Tehran, Iran.

ABSTRACT
In the present study the penetration of grout in a rock joint is simulated using Computation Fluid Dynamics (CFD) and the two-phase finite volume numerical method. Also the fluid flow is considered as a transient flow. The grout is simulated as a real Bingham fluid using Herschel-Bulkley model. Applying saw-cut joints, various joint matedness and different tooth numbers in a specific joint length and changing the tooth height, the effect aperture variation and relative roughness are investigated. The results indicate that the penetration length is under the influence of fluid viscosity, joint aperture, grouting pressure and the grout yield stress. With increasing fluid viscosity, the penetration length decreases and the grouting time increases. The grout yield stress variations resulting more effect on the grout penetration length rather than the viscosity changes. Moreover the results indicate that the joint section was not completely filled by grout and in this simulation the penetration progress in the joint is cleanly illustrated. Decreasing of the joint matedness causes low grout penetration length. Decreasing the tooth height and the tooth numbers in a specific length leads in to low roughness of rock joint. The grouting penetration length shows more sensitivity to aperture changes to roughness changes.

ARMA 10-253

Ultimate Bearing Capacity of Jointed Rocks as Homogenous Media

Fahimifar, A. And Imani, M.
Department of Civil and Environmental Engineering, Amikabir University of Technology, Tehran, Iran

Sharifzadeh, M.
Department of Mining and Metallurgy Engineering, Amikabir University of Technology, Tehran, Iran

ABSTRACT
In this paper the bearing of a jointed rock foundation was investigated using the code UDEC. The models include two joint sets with variable orientations and different joint spacing. Three values for orientation and joint spacing were selected and bearing capacity analysis was performed for each case. The results obtained from the numerical analyses were compared with the existing solutions in which both the rock matrix and joint properties are considered and then, the ranges in which the UDEC simulation takes the best agreement with the existing methods are specified. In other part of this paper, the effect of joint normal and shear stiffnesses on the bearing capacity was investigated. Results of this part show that the joint normal and shear stiffnesses don't have very significant effects on the bearing capacity of rock masses. The results obtained in the research show that by increasing the number of joints beneath the foundation, the bearing capacity will be reduced.

ARMA 10 - 260

Chemo-mechanical Effects on Rock Behavior

Josh Thompson
University of Utah

ABSTRACT

The effect of fluids on rock stiffness, strength, and fracture is complicated and not well understood. Yet many applications involving rock-fluids interaction are of considerable interest, and often pose significant physical and economical impact on a given project. For example, the instantaneous penetration rate during drilling, the formation of complex hydraulic fractures in highly heterogeneous formations, sand production that occurs with increasing water cut, as well as compaction and subsequent subsidence during water flooding in certain formations are of significant interest. There is substantial literature showing the effect of aqueous fluids contacting certain clays, and more limited and scattered literature showing the effect of fluids on strength of various rocks. Mechanisms of strength gain or loss have considered in a few cases capillary effects, pore pressure build-up or reduction, and thermal expansion/contraction in certain rocks. Mechanisms of strengthening/weakening and stiffening/ softening of rock, associated with contact with various solvents or additives have received less attention. Experimental tests were carried out to assess the role of various fluids on the stiffness and strength of three rock types—a weakly consolidated Morrison formation sandstone (a very weakly clay-cemented, fine-grained sandstone), Indiana limestone, and a variant of Berea sandstone. Stiffness and strength alteration as a function of fluid and exposure time were evaluated. Oven dried, deionized water saturation, odorless mineral spirit saturation, and combinations of these were considered. A number of triaxial tests to high pressures were conducted. Additionally, a new form of continuous profiling using a scratch testing concept was performed on slabs saturated with the various fluids to assess global and local variations of strength. Results are provided, showing substantial impact from water alone and less for the specific hydrocarbon saturants considered. Generally, the degree of saturation was not found to be significant - in all cases drained conditions were maintained. Hypotheses for chemical interactions that occurred are provided, suggesting why aqueous compounds can substantially alter strength even in clay-poor rocks.

ARMA 10-285

Is that Frac Job Really Breaking New Rock or Just Pumping Down a Pre-Existing Plane of Weakness?—The Integration of Geomechanics and Hydraulic-Fracture Diagnostics

Mullen, Mike
Halliburton, Denver, Colorado, U.S.A.

Enderlin, Milt
Texas Christian University and Gearhart Industries, Ft. Worth, Texas, U.S.A.

ABSTRACT

With all that horsepower sitting on location, shaking the ground while pumping a frac job, it is hard to imagine that the treatment is doing anything but creating a linear elastic mode-one fracture. However, hydraulic fracturing is far from an exact science because it is difficult to see what the fracturing treatment is doing downhole. Whether it is breaking into new rock in a linear elastic mode or just opening pre-existing planes of weakness in the reservoir to the wellbore, both situations could be beneficial. If the rock is failing down pre-existing planes of weakness, two cases have been observed: (1) a situation where natural fractures that are open and critically stressed, which open below closure pressure and (2) a situation where planes of weakness are open as pressure is exerted on the formation by the frac treatment. The results of both of these cases cause misleading fracturediagnostic interpretation, high leakoff, narrower than expected fractures, frac screenout, and/or complex fracture geometry. When the frac treatment is breaking new rock, the frac treatments pump to completion as designed. In reality, many frac jobs are a combination of these two scenarios, as witnessed by post-frac radioactive tracer logs and by downhole microseismic surveys during the frac treatment. Tracer surveys have limited depth into the formation, but microseismic surveys, which cover a much larger area around the borehole, tend to see a rather large stimulated reservoir volume with greater width and shorter lengths than what is modeled in hydraulic-fracture simulators. If the fracture treatment is breaking new rock, the created fracture will tend to be more like what is modeled in current fracture-simulation models. A novel concept using the diagnostic fracture-injection test or the main frac treatment to integrate the geomechanically determined stress state of the rock with hydraulic-fracture diagnostics has been developed. By comparing the estimates of minimum horizontal stress from both disciplines, one can achieve a better understanding of what the frac treatment is doing downhole and improve the post-stimulation analysis or trouble-job analysis.

ARMA 10-316

Contact Theory for Deformable Blocks in Three-Dimensional Discontinuous Deformation Analysis (3-D DDA)

Beyabanaki, S.A.R.
Pooyesh Rah Mandegar Consulting Engineers, No. 48, Shahr-Tash Alley, North Sohrevardi Avenue, Tehran, Iran

Yeung, M.R.
Department of Civil Engineering, College of Engineering, California State Polytechnic University, 3801 W. Temple Avenue, Pomona, CA 91768, USA

Mohammadi, S.
School of Civil Engineering, University College of Engineering, University of Tehran, Tehran, Iran

Gao, Y. N.
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, Jiangsu 221000, China

ABSTRACT
In this study, contact theory (including contact detection and mechanics) of deformable blocks in nth-order Three- Dimensional Discontinuous Deformation Analysis (3-D DDA) is presented. When high-order 3-D DDA is employed, block faces may deform and not remain planar. In this case, conventional contact models cannot be used. To deal with this difficulty, the authors propose a simple technique. In this research, formulations of stiffness and force matrices in nth-order 3-D DDA due to normal and shear contact forces are presented, as well. One illustrative example is used to validate the new formulations and codes for high orders of displacement functions.

ARMA 10-378

Micro-Indentation Tests to Evaluate Micro-Scale Mechanical Properties Of Granites

Araki, H.
Dept. of Civil Engineering, University of Tokyo, Bunkyo, Tokyo, Japan

Hasegawa, S.
Dept. of Safety Systems Construction Engineering, Kagawa university, Takamatsu, Kagawa, Japan

ABSTRACT
The strength of intact rock has been used widely for the evaluation of rock properties for excavation. However, the performance of boring and excavation of a rock mass is affected by not only its compression strength but also the comprehensive characteristics including the type and mechanical properties of rock-forming minerals. In this study, three kinds of granites were evaluated based on general properties as the intact rock and micro-scale mechanical properties of the rock-forming minerals contained in rocks. Micro-scale properties such as hardness and Young's modulus of grains of quartz and feldspars were measured by the depth sensing indentation test (DSI test). The DSI test, a kind of indentation hardness test, is the technique that measures continuously indentation load and indentation depth in pushing a very small indenter into a surface of a specimen. As a result, micro-scale mechanical properties of the granite which was difficult to excavate by tunnel boring machine were heterogeneous significantly though those of same kinds of minerals that were contained in common granites were roughly uniform.

ARMA 10-436

A Geomechanical Model of the Bakken Petroleum System

Havens, J.B. and Batzle, M.
Colorado School of Mines, Golden, CO, USA

ABSTRACT
The economical success of wells drilled in the Bakken Formation rest heavily on the production strategies. The study described in this paper will aim at improving understanding of in-situ stress and mechanical properties to improve drilling strategies. Strength tests have been conducted on facies D using the Colorado School of Mines facies description. The

Mohr- Coulomb (MC) failure criterion has been implemented and the parameters and ci have been calculated to be 53º and 46MPa respectively. The static Young's Modulus has been calculated to be 21GPa. Tests at higher confining pressure need to be done to get values more representative of subsurface conditions.

ARMA 10-453

Biot Critical Frequency Applied as Common Friction Factor for Chalk with Different Pore Fluids and Temperatures

Andreassen, K.A. and Fabricius, I.L.
Technical University of Denmark, Kgs. Lyngby, Denmark

ABSTRACT
Injection of water into chalk hydrocarbon reservoirs has lead to mechanical yield and failure. Laboratory experiments on chalk samples correspondingly show that the mechanical properties of porous chalk depend on pore fluid and temperature. Water has a significant softening effect on elastic properties of chalk as calculated from wave data, and the softening increases with increasing critical frequency as defined by Biot. The critical frequency is the highest frequency where wave propagation is controlled by solid-fluid friction. The Biot critical frequency is thus a measure of this friction and we propose that the fluid effect on mechanical properties of highly porous chalk may be the result of liquid-solid friction. Applying a different strain or stress rate is influencing the rock strength and needs to be included. The resulting function is shown to relate to the material dependent and rate independent b-factor used when describing the time dependent mechanical properties of soft rock or soils. As a consequence it is then possible to further characterize the material constant from the porosity and permeability of the rock as well as from pore fluid density and viscosity which is highly influenced by temperature.

ARMA 10-454

The Role of Chemical Compaction in the Evolution of Permeability and Strength in Granular Aggregates

Zheng, Baisheng
Department of Energy and Mineral Engineering and G3 Center, PSU, University Park, PA,USA and
School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu, China, 221008

Elsworth, Derek
Department of Energy and Mineral Engineering and G3 Center, PSU, University Park, PA,USA, 16801

ABSTRACT
Dissolution and precipitation of mineral constituents may have a significant influence on the evolution of the mechanical and transport properties of granular aggregates pushed far from equilibrium. They are major porosity-altering processes that operate in many sedimentary rocks. In addition, they may control the build-up and release of fluid pressures in sedimentary basins and along fault zones. Understanding these physicochemical processes is critical in determining the diagenetic and deformational history of rocks and their potential as hydrocarbon reservoirs. Grain intergrowths accelerated by chemical and stress effects increase compaction, reduce porosity and permeability and may augment strength and stiffness. Precipitated mineral matter may similarly occlude pore throats and alter the capillary and permeability of the aggregate. In this work, we explore the magnitude of these effects by representing grain-grain bonding and intergrowth during compaction and fluid circulation using a granular mechanics model (PFC). Grain intergrowth is accommodated by effective dissolution at grain contact points: temperature and local stress control dissolution rate relative to a critical stress that initiates dissolution. Grain-grain contacts are represented by contact stiffness in parallel with a variable rate damping connection to represent creep intergrowth effects. The redistribution of mineral matter is accommodated by diffusion and subsequent precipitation. Diffusion transports dissolved mater from the interface to the pore space, and then precipitates mineral at the less-stressed surface of the grains. Precipitation rate is indexed through aqueous concentration relative to equilibrium concentration through a rate constant.

ARMA 10-508

Consideration of Dilatancy Angle in the Ground Response Curve of Rock Masses

Kargar, A.R. & Rahmanejad, R.
Department of Mining Engineering, Shahid Bahonar University of Kerman, Iran

ABSTRACT
This paper discusses about the effect of dilatancy angle in the ground response curve in homogenous and isotropic rock masses. A numerical method proposed by brown et al. (1983) was implemented in this study by including the effects of elastic strain increments and variable dilatancy angle within a plastic region.

ARMA 10-514

Splitting Failure Criterion and its Application In Pubugou Underground Cavern Groups of China

Xiaojing Li, A.B.
The State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, P.R. China and School of Civil Engineering, Shandong Jianzhu University, Jinan, P.R. China

Weimin Yang &Weishen Zhu
Geotechnical & Structural Engineering Research Center, Shandong University, Jinan, P.R of China

ABSTRACT
The splitting failure happened frequently in the high wall of underground caverns of power station in China. It heavily threatened the stability of surrounding rock mass. In this paper, the splitting failure was studied under the background of large scale underground cavern group of Pubugou hydropower station. The cavern group was located in the canyon surrounded by high mountains. The in-situ stress was very high, whose maximum value was 37 MPa. Under such a condition, the brittle splitting failure phenomena emerged easily. The in-situ investigation showed that large number of splitting cracks appeared in the main power house and transformer chamber. The force of rock bolt and cable had exceeded the design limit severely. In this study, the borehole TV and sliding micrometer were used to observe the splitting crack distribution and measure the displacements. The in-situ test results were compared to the criterion proposed by the author and numerical analysis results. They matched well to some extent. It was helpful to predict the splitting failure using the proposed criterion, so as to amend the excavation scheme and carry out reinforced measure.

SESSION 10—ROCK CHARACTERIZATION III: LOGGING AND LABORATORY CORRELATIONS

ARMA 10-422

Pressure Solution Models for Quartz Materials: Micromechanical Development and Potential Impact in Fractured Reservoirs

Taron, J.
Helmholtz Center for Environmental Research, 04318 Leipzig, Germany

Elsworth, D.
Department of Energy and Mineral Engineering, Penn State University, University Park, PA 16802

Kolditz, O.
Helmholtz Center for Environmental Research, 04318 Leipzig, Germany

ABSTRACT
Pressure solution creep is an important contributor to permeability and porosity change in the upper crust. Engineering projects such as enhanced geothermal systems and petroleum extraction are impacted in the short- and long-term by changes in porous and fracture permeability, and are expectedly influenced by similar creep processes. Of currently available models for pressure solution, few are extendable for variable conditions of stress and temperature, and none have successfully constrained final (equilibrium) compaction magnitudes. With past models and experiments primarily focused on granular media, behavior in fractures remains largely untested at pore or reservoir scale. In this work, a micromechanical model is developed for pressure solution creep that maintains complete dependence on aqueous concentrations and is

transferable for arbitrary conditions of stress and temperature. Equilibrium compaction is constrained with a form of "critical stress"; dependent on conditions of pore structure and applied effective stress. Compared to laboratory experiments on granular quartz, predictions are accurate across a range of conditions (400-500°C, 20-150 MPa, and mean particle diameter of 3-120μm). The model is applied to rough fractures to illustrate important feedbacks between elastic deformation and chemical-mechanical creep. Probing analyses of environments typical of enhanced geothermal systems indicate potential importance for pressure solution, particularly following events that disrupt reservoir equilibrium.

ARMA 10-303

Statistical Analysis of the Effects of Mineralogy on Rock Mechanical Properties of the Woodford Shale and the Associated Impacts for Hydraulic Fracture Treatment Design

Khodir Aoudia and Jennifer L. Miskimins
Colorado School of Mines, Petroleum Engineering Department, Golden, Colorado, USA

Nicholas B. Harris
University of Alberta, Department of Earth and Atmospheric Sciences, Edmonton, Alberta, CANADA

Cheryl A. Mnich
Colorado School of Mines, Geology and Geological Engineering Department, Golden, Colorado, USA

ABSTRACT

Multivariate statistical analysis techniques, including factor, cluster, and multivariate regression analysis, are used to relate 36 different components of a 260 ft core section from the Woodford shale, western Texas, including total organic content (TOC), rock mechanical properties, and geochemical data. The statistical analysis shows that Poisson's ratio is most strongly influenced by clay and quartz content and to a lesser extent TOC. Similar results are seen for Young's modulus measurements. The mechanical properties and mineralogy of the Upper Woodford zone suggest it is the most brittle interval and is most prone to hydraulic fracturing. Hydraulic fracture modeling results indicate that upward growth from the Upper Woodford interval can be expected and that the Middle Woodford zone is less conducive to hydraulic fracturing. The results of the rock mechanical multivariate statistical analysis partially explain the hydraulic fracture modeling outcomes.

ARMA 10-443

A Comparison of the Normal Stress And Hydraulic Conductivity Coupling for Fractures in the Laboratory and In-Situ

Martin, C. D.
University of Alberta, Edmonton, Canada

Eriksson, L. O.
Chalmers University, Göteborg, Sweden

Christiansson, R.
SKB, Stockholm, Sweden

Andersson, J.
Streamflow AB, Stockholm, Sweden

ABSTRACT

The coupling between hydraulic conductivity and normal stress along a discrete fracture has been developed from laboratory tests on small-scale samples. Those results for crystalline rock show a strong coupling between flow and normal stress, particularly when the normal stress is less than approximately 10 MPa. The flow for 611 discrete fractures was determined at the Forsmark site over depths ranging from 100 to 800 m. The orientation of the these discrete fractures were determined using Bips images and the normal stress acting on the fracture calculated from the in-situ stress model for the site. The strong coupling between stress and flow observed in small-scale laboratory tests is not supported by the in situ results.

ARMA 10-404

Mechanical and Acoustical Properties Of Sand - Clay Mixtures under Stress

Bhuiyan, M. H., Kolstø, M. I.
NTNU, Trondheim, Norway

Holt, R.M.
NTNU and SINTEF Petroleum Research, Trondheim, Norway

ABSTRACT
The importance of understanding static and dynamic mechanical behavior of soft sands and clays has industrial relevance towards e.g. development of unconventional petroleum reservoirs as well as underground storage of CO2. Experiments on controlled mixtures of sand – clay mixtures are presented here, mostly performed within a uniaxial strain set-up (oedometer) below 10 MPa axial stress. The data illustrate how clay content impact on compaction behavior as well as on stress, pore pressure and stress path dependence of wave velocities and velocity anisotropy. The data show characteristic differences between materials in which sand is load bearing versus those where clay is the load-bearing phase.

ARMA 10-272

Quantifying and Linking Shale Properties at a Variable Scale

Diaz, E., Sisk, C. and Nur, A.
Ingrain, Inc., Houston, TX, USA

ABSTRACT
At least three characteristics of shale are key to asset evaluation and development: the presence of organic matter and free gas; the porosity and permeability of the shale matrix; and the susceptibility of the matrix to fracturing. Only a favourable combination of these three factors allows for discriminating good from poor shale reservoir. How to quantify these factors at the early stage of field evaluation and then use them for long-term field production and development? One way of addressing this challenge is by using computational rock physics. Specifically, the volume of hydrocarbons in place is quantified from multiple high-resolution 3D nano-scale images of shale fragments. The same images can be used to compute porosity and the directional gas or oil permeability of shale. Finally, the brittleness of shale is likely to be related to its mineralogy, specifically the amounts of silica and carbonates. This mineralogy is quantified in a range of scales: (a) at a nanoscale by image-processing microscopic 3D images to highlight the principle constituents and (b) at the core scale by using dualenergy X-ray CT scanning that supplies the bulk density and the atomic number logs. The dual-energy core-scale scanning combined with well logs and traditional visual inspection gives an overall picture of macroscopic heterogeneity of the rock under examination. This scanning points to the locations where micro- and nano-scale tests have to be selected for computing the bulk and transport properties. Finally, by integrating measurements of total organic content, porosity, and permeability at the nano-scale with the shale units segregated using the core-scale measurements, a range of heterogeneity scales present in any natural rock, especially in shale, is cover.

ARMA 10-196

Petrophysical Methodology for Predicting Compressive Strength in Siliciclastic "Sandstone-to-Shale" Rocks

Crawford, B.R.
ExxonMobil Upstream Research Company, Houston, TX, USA

Gaillot, P.J. and Alramahi, B.
ExxonMobil Upstream Research Company, Houston, TX, USA

ABSTRACT
An extensive database of mechanical strength measurements has been compiled for sandstone-to-shale siliciclastic rocks including detailed petrographic and petrophysical characterization. The database comprises ~80 distinct lithologies and ~600 discrete triaxial compressive strength tests and is subdivided into 3 generic lithotypes on the basis of fine-grained matrix volume fraction as determined from thin-section point counting. An automated surface fitting procedure has been used to derive a new generic algorithm for predicting rock shear strength as a function of lithotype (arenite, wacke or shale) porosity and normal stress magnitude. The probable error (50% confidence limit) associated with mean shear strength prediction has been quantified as a function of all input variables. Additional predictive algorithms have also been gener-

ated that relate the Mohr-Coulomb failure parameters (cohesion and internal friction angle) to porosity and the total clay weight fraction as derived from X-ray diffraction analysis. Thus siliciclastic rock strength is potentially predictable from routine characterization of core or cuttings or remote sensing associated with geophysical wireline logs and seismic inversion. Log-based case studies are described which outline the petrophysical workflow for generating mechanical stratigraphy from routine formation evaluation.quantified from multiple high-resolution 3D nano-scale images of shale fragments. The same images can be used to compute porosity and the directional gas or oil permeability of shale. Finally, the brittleness of shale is likely to be related to its mineralogy, specifically the amounts of silica and carbonates. This mineralogy is quantified in a range of scales: (a) at a nanoscale by image-processing microscopic 3D images to highlight the principle constituents and (b) at the core scale by using dualenergy X-ray CT scanning that supplies the bulk density and the atomic number logs. The dual-energy core-scale scanning combined with well logs and traditional visual inspection gives an overall picture of macroscopic heterogeneity of the rock under examination. This scanning points to the locations where micro- and nano-scale tests have to be selected for computing the bulk and transport properties. Finally, by integrating measurements of total organic content, porosity, and permeability at the nano-scale with the shale units segregated using the core-scale measurements, a range of heterogeneity scales present in any natural rock, especially in shale, is cover.

ARMA 10-167

Comparison of Methods to Derive Rock Mechanical Properties from Formation Evaluation Logs

Woehrl, B.
Baker Hughes, D-29221 Celle, Germany

Ruhr-University Bochum, Institute of Geology, Mineralogy and Geophysics, D-44780 Bochum, Germany

Wessling, S., and Bartetzko, A.
Baker Hughes, D-29221 Celle, Germany

Pei, J.
Baker Hughes, Houston, Texas 77073-5114, USA

Renner, J.
Ruhr-University Bochum, Institute of Geology, Mineralogy and Geophysics, D-44780 Bochum, Germany

ABSTRACT
Rock mechanical properties may be derived from formation evaluation logs using empirical relations or using algorithms based on microscopic rock models, which relate the dynamic deformation behavior of the rock to the static deformation behavior. In this study, we compare both approaches. In a first step, the algorithm FORmation MEchanics Logging (FORMEL) is fed with synthetic data sets for sandstones and shales to determine the sensitivity of the algorithm for variations in the input data (porosity, compressional slowness, density). The UCS, Young's modulus and bulk modulus calculated from FORMEL are compared with results from empirical relations. In a second step, the FORMEL calculated rock mechanical parameters are compared with data from triaxial tests on different sandstones and the Woodford shale. This study shows that variations in petrophysical input parameters have a large influence on the FORMEL results and conclude that models relating on more than one input parameter are preferred over empirical relations which relate rock mechanical parameters to only one value. The differences between laboratory analyses and calculations using FORMEL indicate that also microscopic models are not universally applicable but need to be calibrated against laboratory test data for different formations.

SESSION 11 — WELLBORE STABILITY I

ARMA 10-153

A Geomechanical Approach to Enhancing Well Design and Increasing Drilling Performance in the Sichuan Xinchang Gas Field, China

Shize Wang, Xinjiang Guo, Yong Li, Jingming Zhong, and Yongzhang Hu
Southwest Engineering Institute of Technology of SINOPEC, Deyang, Sichuan,China

Zhibin Yang
Chengdu University of Technology of China, Engineering Technology Institute of Southwest Petroleum Branch, SINOPEC ,Chengdu, Sichuan, China

Yonggui Guo and Lisa Dell'Angelo
GeoMechanics International, Houston, Texas, U.S.A.

Yongsheng Zhou
GNT, Beijing, China.

ABSTRACT
The Xinchang gas field is characterized by multiple over-pressured gas formations that are composed of hard, fractured rocks. Optimizing the mud weight and well design to improve drilling speed and reduce non-productive time is challenging in this reservoir. In 2007, we built a Geomechanical model based on a detailed quantitative analysis of the rock properties, pore pressure, and stress state in the study wells (including borehole collapse pressure and fracture gradient). The interpreted strike-slip stress regime (Shmin < SV < SHmax) was validated in 2008 by the deadly 8.0 magnitude Sichuan earthquake. We used the geomechanical model to simplify the casing design by eliminating one casing string and to optimize mud weight for a new well which was successfully drilled without any major drilling problems. The average ROP was nearly doubled to 2.95m/h and drilling time was significantly reduced (133 days compared to previous 339 days). The well is now producing gas at 10.3×104 m3/d. The study demonstrates the robustness of stress state and rock strength determination based on modeling the co-occurrence of breakouts and drilling induced tensile fractures. The paper highlights the importance of correlating data from different sources to confirm the accuracy of the geomechanical model.

ARMA 10-283

Changing the Safe Drilling Window with Invert Emulsion Drilling Fluids: Advanced Wellbore Stability Modeling Using Experimental Results

Terry Hemphill
Halliburton, Houston, Texas, USA

William Duran
Saudi Aramco, Abqaiq, Eastern Province, Saudi Arabia

ABSTRACT
In today's increasingly complex well designs, often the range in drilling fluid densities required to prevent hole collapse without fracturing the wellbore, i.e., the safe drilling window, is narrow. This is often the case for wells having high angles of deviation, and is of particular concern in extended-reach drilling (ERD) wells. With increasing step-outs, the drilling equivalent circulating density (ECD) continues to climb with increasing measured depth (MD) while the true vertical depth (TVD) remains fairly constant. The net result can be that as horizontal departure lengths continue to increase, the drilling ECD violates the safe drilling window. A recent study was presented to the industry, in which the effect of changes in the water phase salinity (WPS) of invert emulsion drilling fluids (IEF) were investigated as a function of rock shear failure for two very different shales: a deepwater West Africa shale and a more-competent Oklahoma shale. After a 3-hr exposure time, the changes in rock strength with different WPS levels were measured directly and results were qualitatively consistent for the two shales. In this paper, the effect of changes in the WPS of IEF on the safe drilling window is demonstrated in an ERD drilling scenario.

ARMA 10-328

The Impacts of Failure Criteria and Geological Stress States on the Sensitivity of Parameters in Wellbore Stability Analysis

Tran, Minh H. & Abousleiman, Younane N.
Mewbourne School of Petroleum Engineering and the PoroMechanics Institute, The University of Oklahoma, Norman, Oklahoma, USA

ABSTRACT
This paper highlights and prioritizes various rock mechanical parameters, in-situ stresses and pore pressure conditions that affect wellbore instability with failure criteria frequently used in such analysis such as the Mohr-Coulomb, Drucker-Prager, modified Lade, and tensile failure. In addition, different far-field stress regimes including the normal fault, thrust fault, and strike-slip fault were considered in this study to evaluate the influence of such geological settings on parameter sensitiv-

ity for each of the failure criterion. The results showed that the magnitude of impact of the various parameters depends on both the failure criterion in use and the regional far-field stress state. In addition, for all shear failure criteria and stress regimes, the maximum horizontal principal stress, SH, and formation pore pressure, Ppore, were shown to have greater effects on collapse mud weight (CMW) compared to the minimum horizontal principal stress Sh. Moreover, while SH is the most sensitive parameter for Mohr-Coulomb criterion in all far-field stress states, Ppore were shown to have the largest effects on the modified Lade criterion regardless of regional stress regimes. The results also showed that among the various rock mechanical properties, the cohesion and friction angle yield greatest influence on CMW analysis. Lastly, the role of formation tensile strength on tensile failure analysis was shown to be subtle compared to in-situ stresses and formation pore pressure for all stress regimes.

ARMA 10-433

Evaluation of Consolidation and Material Yielding during Underbalanced Drilling Well in Shale - A Numerical Study

Islam, M.A., Skalle, P.
Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology, NTNU,Trondheim, Norway

Søreide, O.k.
STATOIL, Trondheim, Norway.

ABSTRACT

Establishment of pore pressure equilibrium in shale is a time dependent process which is governed by shale's intrinsic properties. The extremely low permeability of shale is a key parameter involved in the consolidation process and restriction of fluid flow (undrained mechanism). Underbalanced drilling in shale usually increases the risk of borehole instability due to yielding or failure of the rock adjacent to the borehole. In addition, shale has both a ductile and brittle nature. Material plasticity is strongly influenced by the consolidation and material dilation process. The distribution of pore pressure is taking a crucial role in the consolidation process, and has to be clarified for undrained mechanism. Therefore, the aim of this work is to quantify pore pressure distribution and material yielding when the borehole reaches underbalanced conditions. The M-C elasto-plastic numerical material model was applied to accomplish the study goal. The simulation results indicated that with decreasing mud pressure increased yielding in the dilating region took place. Time delayed pore pressure distribution is influenced by material dilation. Pore pressure distribution behaved anomalously after yielding. Here the dilating angle seemed to be the critical parameter. The outcome of this study will help to understand the physics of material yielding and the impact of consolidation on time delayed borehole instability.

ARMA 10-142

Mechanical Behavior of Concentric Casing, Cement, and Formation Using Analytical and Numerical Methods

Jo, H.
BJ Services Company, Houston, Texas, USA

Gray, K.E.
The University of Texas at Austin, Austin, Texas, USA

ABSTRACT

The primary goal of this research is to develop comprehensive analytical and numerical models for stress distributions around an inclined, cased wellbore by considering all wellbore processes, including amendments to models of other works. Most previous research has focused on individual wellbore processes rather than a comprehensive treatment which considers all wellbore processes simultaneously: a more realistic approach developed in this paper. To achieve this goal, this work utilizes an elastic approach by coupling a poroelastic, undrained condition and a steady state condition for stresses induced by wellbore temperature variations. The superposition principle is used to develop a comprehensive model, which is then applied to cement sheath failure. ABAQUS1 is utilized for numerical solutions to verify the comprehensive analytical model. These comprehensive models show analogous stress distribution results to those of previous models at each individual wellbore process when using the plane strain condition. However, ABAQUS model results show stress differences because the general plane strain model for the analytical solution and full 3D model for numerical solution are used. While there are differences between analytical and numerical solutions as noted, the comprehensive analytical model is a good alternate to costly numerical software programs, and it provides an improvement to plane strain models.

ARMA 10-477

The Effect of Horizontal Completions on the Breakdown Pressures of Anisotropic Gas Shales

Deenadayalu, C. and Suarez-Rivera, R.
TerraTek, A Schlumberger company

ABSTRACT
It is said that unconventional gas shales are easy to find but difficult to fracture. This is so because of the very large surface area (1 to 10 million square feet) required in these ultra low permeability systems for gas production at economic rates, and the problems associated to create it and maintain it. Successful hydraulic fracturing in these reservoirs requires understanding of near-wellbore conditions of perforation, fracture initiation, and near-wellbore fracture tortuosity. It also requires understanding of far-field conditions of fracture containment, fracture complexity, proppant transport, and rock-fluid interactions. Unfortunately maintaining the created surface area bounded within the reservoir section is typically problematic. More importantly, the low proppant carrying capacity of slick water and the tortuosity of the fracture geometry results in poor proppant transport and placement. This leads to considerable loss of surface area and fracture conductivity during production, thus the challenge. In this paper we concentrate on the development of hoop stresses in horizontal wells as a function of the type of completion (cased hole or open hole), and time (creep). We show that the wellbore hoop stresses are significantly affected by the quality of the cement job (cased and cemented completions). Mud channeling during displacement results in uneven support at the formation/casing interface, and leads to considerable changes in the hoop stresses, and the associated breakdown pressures for fracture initiation. We conclude by stating that understanding these effects will result in better decisions and better near-wellbore conditions for fracture initiation.

ARMA 10-432

Stability Analysis in Shale through Deviated Boreholes using the Mohr and Mogi-Coulomb Failure Criteria

Islam, M.A., Skalle, P.
Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology, NTNU, Trondheim, Norway

Al-Ajmi, A.M.
Department of Petroleum and Chemical Engineering, Sultan Qaboos University, Oman

ABSTRACT
Borehole collapse is a commonly encountered wellbore stability problem during drilling in shale. Borehole failures can be reduced by determining the proper mud pressure based on the selection of an appropriate rock failure criterion. Several linear elastic constitutive models have been tested to predict borehole collapse pressure (CP). The fore most used criterion for brittle failure of rocks is the Mohr-Coulomb (M-C), Mogi-Coulomb, Modified Lade and Drucker–Prager. It is seen that either numerical or closedform analytical solutions of these constitutive models are the preferred way to predict CP. But, closed-form analytical solution for deviated wells under anisotropic stress state is a tedious task and a simple mathematical expression can not be reached. This study evaluated a simplified closed-form M-C analytical solution, including mud cooling effects and compared the results with existing solutions. Existing solution was obtained through the Mogi Coulomb model. It is a 3D analytical model, using linear elasticity theory to estimate the CP from a rock model. Moreover, a standard work flow of how the Mogi-Coulomb numerical model can be evaluated with triaxial instead of polyaxial test data was reviewed. Shale characterization experimental data were used to estimate model fitting parameters of the Mogi-Coulomb model. Finally, a comparative field case study was carried out to enhance the confidence of using the appropriate material elastic constitutive model for borehole stability analysis. The M-C closed-form analytical solution is providing almost similar prediction as Mogi-Coulomb numerical solution under weak in-situ anisotropy. It was found that well trajectory factors are more vital than the effect of intermediate stress effect on CP.

SESSION 12 —COUPLED PROCESSES I

ARMA 10-292

Simulation of Fluid Flow in a Naturally Fractured Poro-thermoelastic Reservoir

Tao, Q., and Ghassemi, A.A.
Harold Vance Department of Petroleum Engineering, Texas A&M University, TX, USA

ABSTRACT
This paper examines the problem of injection/extraction into a naturally fractured rock while considering the role of poro-thermoelastic processes and joint deformation on reservoir permeability change and fracture pressure variation. This is accomplished by considering fluid flow and heat transport in a 2D model of a fracture network that is based on the displacement discontinuity technique. It is assumed that the fracture aperture and joint deformation are significantly less than the joint lengths, there are a large but finite number of joints, and fluid in the fractures is compressible. The total normal stress in the direction normal to the joint varies non-linearly but, in the shear direction the joint stresses are proportional to deformation when the deformation are in the elastic range, and the joint dilation is considered. Numerical experiments are presented to illustrate the role of poro-thermoelatic effects as well as joint constitutive behavior on the reservoir response to injection and extraction.

ARMA 10-327

3D Poroelastic Analysis of Natural Fracture Response to Variable Injection/Extraction Rates

Safari, M.R. and Ghassemi , A.
Department of Petroleum Engineering at Texas A&M University, College Station, Texas, U.S.A

ABSTRACT
The deformation response of natural fractures is important to design of geothermal and petroleum reservoirs stimulation and the measurement of the in-situ stress. In this aspect joint deformation characteristics as well as the rock poroelastic properties can play key roles in the interpretation of the pressure history and its analysis. In this work, a three-dimensional poroelastic displacement discontinuity model is developed for modeling natural and induced fractures in rock. The model is poroelastic, and considers the geometric nonlinearity of the joint deformation, temporal variation of the injection/extraction rates, and pressure-dependent leak-off. After theoretical descriptions and presentation of some aspects of model development, examples are presented to highlight the versatility of the method and the role of poroelastic effects, joint deformation characteristics in injection/extraction operations such as a Huff-Puff test, and to illustrate the post-stimulation behavior of a natural fracture.

ARMA 10-337

A Chemo-poroelastic Solution for Pore Pressure Transmission Test Considering Solute Diffusion

Jian Huang & Ahmad Ghassemi

Texas A&M University, College Station, TX, USA

ABSTRACT
A pressure transmission test is usually used to characterize shales swelling characteristics by interpreting the test results using a chemo-mechanical theory. This paper presents aspects of the development of an analytical solution for modeling and analysis of a pressure transmission test within the framework of a fully coupled chemo-mechanical theory based on irreversible thermodynamics. The solution provides the time history of pore pressure and solute concentration in the sample using different downstream boundary conditions namely, zero-flux and constant pressure. The analytical solution is verified by comparison with available data and model predictions are described with reference to the shale swelling and transport properties and the characteristics of the theoretical framework.

ARMA 10-480

A Multi-Scale Micromechanics Framework for Shale Using Nano-Tools

Ortega, J. A. and Ulm, F.-J.
Massachusetts Institute of Technology, Cambridge, MA, USA

Abousleiman, Y.
University of Oklahoma, Norman, OK, USA

ABSTRACT
The successful prediction of poroelastic properties of fine-grained rocks such as shale continues to be a formidable challenge for the rock mechanics community. The highly heterogeneous nature of shale in terms of its compositional and microstructural features translates into complex anisotropic behaviors at different scales. The recent application of instrumented indentation for the mechanical characterization of shale has revealed a granular response and intrinsic anisotropy of its porous clay phase at nanometer length scales. The discovered grain-scale behaviors have been incorporated into a multi-scale micromechanics model for shale poroelasticity. The inputs to the model are two volumetric parameters synthesizing mineralogy and porosity information. The model was calibrated and validated with independent data sets of anisotropic elasticity obtained from nanoindentation and standard laboratory acoustic experiments for shale specimens with and without organic content. The intrinsic elastic anisotropy corresponding to the porous clay phase delineates the overall anisotropy of shale observed at macroscales. The model represents a useful tool in rock mechanics applications for the prediction of shale acoustic properties based on material composition and porosity data.

ARMA 10-455

Stabilization Procedures in Coupled Poromechanics: A Critical Assessment

Preisig, M. and Prévost, J.-H.
Princeton University, Princeton, NJ, USA

ABSTRACT
Numerical solutions for problems in coupled poromechanics suffer from spurious pressure oscillations when small time increments are used. We present an overview of stabilization methods that in our view are promising. In particular we investigate the fluid pressure laplacian stabilization (FPL) and a method derived by using finite increment calculus (FIC). On a simple 1D test problem we investigate stability of the two methods. While the analysis reveals that FIC stabilizes the pressure for all time step sizes, it leads to a definition of the stabilization parameter in the case of the FPL stabilization. Numerical tests in one and two dimensions on 4-noded bilinear and linear triangular elements confirm the effectiveness of both the FPL and the FIC stabilization schemes. A bearing capacity analysis demonstrates that the FPL-method also works for non-linear material behavior.

ARMA 10-423

Mechanisms for Permeability Evolution in Fracture Networks: Hydrothermal Effects in Enhanced Geothermal Systems

Taron, J.
Helmholtz Center for Environmental Research, 04318 Leipzig, Germany

Elsworth, D.
Department of Energy and Mineral Engineering, Penn State University, University Park, PA 16802

Kolditz, O.
Helmholtz Center for Environmental Research, 04318 Leipzig, Germany

ABSTRACT
Dominant mechanisms for permeability change in hydrothermal fracture networks are driven by the combined action of thermal, hydrologic, mechanical, and chemical forces. Potential mechanisms include, but are not limited to, thermo-mechanical deformation, mineral reaction, shear dilation, and chemical-mechanical creep. While some effort has been devoted to examining each of these processes individually, magnitudes of relative interaction remain poorly constrained at small- and large-scale. In this work, a numerical simulator is used to model these processes at reservoir scale. Permeability and porosity are modified as fractures dilate or contract under the influence of pressure solution creep, thermo-hydro-mechanical compaction/dilation, and bulk mineral reaction in a deformable, dual-porosity medium. Simulations focus on a prototypical enhanced geothermal system as cold (70°C) water is injected at geochemical disequilibrium within a heated reservoir (250°C). For an injector withdrawal doublet, separated by 500m, the results demonstrate the strong influence of mechanical effects in the short term (several days), the influence of thermal effects in the intermediate term (<1 month at injection), and the prolonged and long-term (>1 year) influence of chemical effects, especially close to injection. Differences are examined between small scale, frequent fractures and large scale, more widely spaced fractures. A contact area based model for pressure solution creep is retrofit into the simulator and results indicate potential importance for pressure solution at reservoir scale. However, an equilibrium simplification is incapable of examining long term compaction trends, and a kinetic based form may be necessary to reproduce these large scale behaviors.

ARMA 10-305

Shaped Charge Penetration into Stressed Rock – Penetration Depth Experiments and Modeling

Harvey, J., Grove, B., and Zhan, L.
Schlumberger Reservoir Completions Center, Rosharon, Texas, USA

ABSTRACT
Explosive shaped charges have been the primary means of creating a flow passage from a hydrocarbon bearing reservoir into a wellbore for almost six decades, and overall well productivity is directly related to penetration depth. While penetration depth performance has improved dramatically over that time frame, current models of penetration are inaccurate. The largest source of error is a direct result of the reliance on unstressed concrete penetration as a measure of downhole shaped charge performance into real rock. Following a brief review and discussion of several industry models, the results of an ongoing experimental program will be discussed. This program has produced several hundred data points spanning multiple shaped charges, rock types and strengths, with liquid and gas pore fluid, and over a range of overburden stresses and pore pressures. This extensive data set has confirmed well-known aspects of the underlying physics, such as the reduction in penetration with increasing effective stress and/or rock strength. Previously unknown aspects have been revealed such as the "ballistic" pore pressure coefficient which is analogous to the quasi-static Biot coefficient. A new correlation is proposed which combines rock strength and stress into a single term. Gas pore fluid in dry sandstone generally results in reduced penetration depth compared to brine saturated sandstone, but the reduction appears to be dependent on rock strength as well. Shaped charge performance into gas saturated rocks was also observed to be less sensitive to effective stress. Rock composition also effects penetration depth, as equivalent strength sandstone and limestone exhibit significantly different penetration depths. A discussion is included regarding the impact of decades of reliance on surface concrete penetration on shaped charge development. A likely shift is predicted within the industry as developers begin to make charges optimized for real rock performance. Surface concrete performance testing is best suited for system-level interference and entrance hole evaluation as originally intended.

SESSION 13—ROCK CHARACTERIZATION IV: FRACTURE MECHANICS--ANALYTICAL AND NUMERICAL

ARMA 10-309

A Nanomechanical Investigation of the Crack Tip Process Zone

Brooks, Z., Ulm, F-J., and Einstein, H.H.
Massachusetts Institute of Technology, Cambridge, MA, USA

Abousleiman, Y.
University of Oklahoma, Norman, OK, USA

ABSTRACT
This study explores the interaction between crack initiation and nanomechanical properties in the crack tip process zone (zone of microcracking at the tip of a propagating crack) of a brittle material. Samples of Carrara marble with pre-existing cracks ("flaws") were loaded in a uniaxial testing machine until the process zone appeared at the tips of the pre-existing cracks in the form of "white patching". Two techniques were then used to obtain nanomechanical properties of the process zone and relate them to macroscale crack initiation: digital photography, to visually assess the macrostructure and crack formation, and nanoindentation, to yield nanomechanical properties and assess nano/microheterogeneities. Nanoindentation testing was comprised of lines and grids of single nanoindentations located both near and far from the process zone. The purpose of nanoindentation testing is to investigate the underlying trend in nanomechanical property change between intact and process zone marble. Analysis of nanoindentation testing results showed a decrease of both modulus and hardness (a) near grain boundaries in intact material, and (b) with closeness to the process zone. Ultimately, the study confirms that the crack tip process zone manifests itself as an area of reduced nanoindentation hardness and nanoindentation modulus in marble.

ARMA 10-363

Numerical Analysis of Multiple Fracture Propagation in Heterogeneous Rock

K. S. Min, Z. Zhang, and A. Ghassemi
Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, USA

ABSTRACT
Hydraulic fracturing in rock often takes a complex form involving multiple fracture propagation resulting from material and stresses heterogeneity. Multiple cracks and crack branching phenomena cause high fracture tortuosity and increased treatment pressure. In this paper, crack propagation by hydraulic pressurization is investigated using a modified Virtual Internal Bond (VIB). Multiple cracks and crack branching behavior are simulated for both homogeneous and inhomogeneous rock. In addition, hydraulic fracture natural fracture interaction is studied with reference to the role of material and stress inhomogeneity, and fracture spacing.

ARMA 10-278

Fracture Re-Initiation as a Possible Branching Mechanism during Hydraulic fracturing

Dahi Taleghani, Arash
Louisiana State University, Baton Rouge, Louisiana, USA

ABSTRACT
Hydraulic fracturing in naturally fractured reservoirs can be significantly different from that in non-fractured reservoirs. New diagnostic tools have verified complicated network of stimulated fractures in naturally fractured reservoirs. Here, we are trying to give a physical explanation of erratic changes in the orientation of hydraulic fracture growth. When hydraulic fractures intersect sealed natural fractures, a kink is formed in the fracture path. These kinks are the locations of stress singularity which makes them a secondary choice for fracture propagation. Results demonstrate that fracture pattern complexity is strongly controlled by the magnitude of anisotropy of in situ stresses, rock toughness, fracture cement strength as well as geometry of natural fractures.

ARMA 10-473

Comparison between Elasto-Plastic and Rigid-Plastic Cohesive Surface Elements and Embedded Strong Discontinuity Finite Element Implementation of Rock Fracture

Regueiro, R.A. and Yu, S.-K.
Department of Civil, Environmental, and Architectural Engineering, University of Colorado at Boulder, Boulder, CO, U.S.A.

ABSTRACT
The paper presents a comparison between embedded strong discontinuity finite element implementation and elastoplastic (EP) and rigid-plastic (RP) cohesive surface finite element (CSE) implementations of cracking/fracture in rock. It is shown that care must be taken when choosing the elastic stiffnesses for the EP CSE model, if they are to act as penalty parameters. The RP CSE and EDE implementations obviate this choice. Formulation and implementation is restricted to small strains and rotations, and numerical examples are conducted for two-dimensional (2D) plane strain.

ARMA 10-468

Numerical Analyses of the Effect Of Heterogeneities on Rock Failure Process

Valley, B.
MIRARCO, Sudbury, Ontario, Canada/CEMI – Center for Excellence in Mining Innovation, Sudbury, Ontario, Canada

Suorineni, F.T.
MIRARCO, Sudbury, Ontario, Canada

Kaiser, P.K.
CEMI – Center for Excellence in Mining Innovation, Sudbury, Ontario, Canada

ABSTRACT
While heterogeneities in strength and deformation properties are thought to play an important role in the failure processes of rocks and rock masses, they are rarely explicitly introduced in numerical models. This paper present the results obtained by introducing heterogeneities in a Finite Element Modeling tool (Phase2TM). Particularly the effect of heterogeneities in rock modulus and strength are investigated at the laboratory test sample scale. Limited modulus variability (coefficient of variation smaller than 1.5%) is sufficient to generate rock behaviour that is highly affected by induced tensile stress conditions. This variability in modulus reduces the peak strength and the post-peak strength drop: with increasing heterogeneity in deformability, the rocks become less brittle (i.e., more strain-softening). However, the brittleness in the low confinement range, leading to spalling behaviour, is enhanced by this heterogeneity. Various loading case and geometries are investigated highlights the influence of rock and rock mass heterogeneities. Modulus heterogeneities generate tensile conditions and damage when taking core samples from relatively high stress conditions. This may influence the samples strength and lead to an underestimation of the in-situ rock strength at depth. Heterogeneities influence the failure pattern around opening, with practical implication on ground support requirements. An equivalent homogeneous properties concept, as used for example by the GSI system, doesn't properly capture the failure pattern generated by the presences of heterogeneities, suggesting that the approach of "equivalent" homogenous material could be inadequate and that heterogeneities should be introduced explicitly in numerical analyses of geomechanics problems.

SESSION 14 — FRACTURING

ARMA 10- 530

Thoughts on Quantitative Field Scale Characterization of Post-failure Rock Mass Conditions and their Influence on Underground Mine Design

W. F. Bawden
Pierre Lassonde Chair in Mining Engineering, Department of Civil Engineering, University of Toronto, ON, CAN

ABSTRACT
Field scale rock mass constitutive behaviour remains an area of intense debate. The Generalized Hoek-Brown [GHB] criterion remains the most popular and commonly used rock mass behaviour criteria for practical applications. The GHB as originally developed did not did not incorporate post-peak behaviour and provides no guidance as to how such parameters should be derived. It is, in fact, uncertain whether derivation of so called post-peak GHB parameters is a valid or appropriate approach, although at present there appears to be few viable alternate options. Numerous attempts have been made to derive post-peak GHB parameters and to use these to model rock mass behaviour in the post failure regime. This paper critically discusses several of these approaches and tests two of these against two field case studies.

ARMA 10- 158

Uncertainty in Estimation of Volumetric Block Proportion of Bimrocks by Using Scanline Method

Tien, Y.M.; Lu, Y. C.; Chung, Y. J; Wu, T. H.
Department of Civil Engineering, National Central University, Jhongli, Taoyuan, Taiwan

Lin, J-S
Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA 15261, USA

Kou, M. C.;
Institute of Nuclear Energy Research, Administration of Atomic Energy Council, Longtan, Taoyuan TAIWAN

Lee, D. H.
Department of Civil Engineering, National Cheng Kung University, Tainan 701, TAIWAN

ABSTRACT
Volumetric block proportion (VBP) is a crucial parameter for assessing the mechanical properties of Bimrocks. The widely used scanline method has been very successful in providing VBP estimates, but the uncertainty for such estimates has only been quantified empirically. This paper presents both analytical and numerical approaches in addressing this issue. Analytical equations were derived for the mean and variance of scanline VBP estimates based upon a representative volume element concept. Extensive numerical simulation was carried that affirmed the analytical solutions. To facilitate a general application, a normalized coefficient of variation equation is given that can be used for assessing the uncertainty of VBP. An illustrated example on its use is given at the end.

ARMA 10-207

The Effect of Different Rock Types and Roller Cone Insert Types and Wear on ROP (Rate of Penetration)

Wu, A., Hareland, G., and Rashidi, B.
University of Calgary, Calgary, Alberta, Canada

ABSTRACT
One way of improving the drilling operation is to utilize drilling simulation software. Modeling the bit performance, ROP (rate of penetration), is an inseparable part of the drilling simulation software. In this paper three main factors affecting ROP are discussed, including rock types (shale and limestone), insert types (Scoop, Chisel, Conical and Ovoid), and insert wear (IADC dull grade). Computer models were developed and simulations are conducted to analyze the three factors' effect on ROP. From these simulations, some interesting results are obtained. The decrease rate in ROP for limestone is greater than that for shale when IADC bit wear increases, but when weight on bit (WOB) is very small, the phenomenon is opposite. The normalized decrease rate in ROP as a function of IADC bit wear for shale is getting smaller with increasing WOB, and the normalized decrease rate in ROP as a function of bit wear for limestone will approximately remain the same for different WOB. This indicates that when WOB is relatively low, the sharpness of insert, or the dull grade, will bring bigger effects on ROP and that the effects on ROP with different dull grades are different for different rock types.

ARMA 10-140

Cohesive Fracture Mechanics Based Analysis to Model Ductile Rock Fracture

Yao Yao, Shekhar V Gosavi, Kevin H Searles, Tim K Ellison
ExxonMobil Upstream Research Company, Houston, TX, USA

ABSTRACT
Most of the hydraulic fracture modeling in the oil industry continues to rely on empirical models, or on numerical methods based on linear elastic fracture mechanics (LEFM). Generally these methods give reasonable predictions for hard (brittle) rock hydraulic fractures. However, for ductile rocks, such as clay or weakly consolidated sandstones (low cohesion granular material), LEFM-based methods typically give conservative predictions on fracture geometry. One of the reasons the LEFM-based methods fail to give accurate predictions for these materials is that the fracture process zone ahead of the crack tip should not be neglected (and can be significant) in ductile rock fracture analysis. Based on the size of the fracture process zone and its effect on crack extension in ductile rock, the fundamental mechanical difference of LEFM and cohesive fracture mechanics-based methods is discussed in this paper. A pore pressure cohesive zone model (CZM) has been developed and applied to predict hydraulic fracturing for injection wells. The cohesive zone method is a numerical tool developed to model crack initiation and growth in quasi-brittle materials considering the material softening effect. The pore pressure CZM has been applied to investigate the hydraulic fracture with different rock properties. The hydraulic fracture predictions of a three-layer water injection case has been compared using pore pressure CZM with revised parameters, LEFM-based pseudo 3D model, a Perkins-Kern-Nordgren (PKN) model, and an analytical solution.

ARMA 10-319

Modeling Surface Heave Induced by Hydraulic Fracturing Stimulation and Co2 Injection into Coal Seams

Li, H.
Alberta Innovates – Technology Futures, Edmonton, Alberta, Canada

Li, G.
Halliburton, Houston, TX, USA

ABSTRACT
To monitor a geomechanical response of injecting CO2 into relatively shallow coal seams, tiltmeters were set as an array to cover the ground surface area surrounding the injection well, and to measure the ground deformation during a well fracturing stimulation and a short-term CO2 injection test. In this paper, an attempt to establish a quantitative relationship between the in-situ coal swelling and the corresponding ground deformation was made by means of numerical simulation study.

ARMA 10-177

Improved Fracture Gradient Methodology—Understanding the Minimum Stress in Gulf of Mexico

Gemma Keaney
Geomech Norge AS Consulting, Bergen, Norway

Gang Li and Ken Williams
Halliburton Consulting, Houston, TX, U.S.A.

ABSTRACT
Over 300 individual leak-off test data from six Gulf of Mexico (GOM) regions were analyzed to derive relationships for fracture gradient across GOM. Analysis of leak-off tests, as a function of the GOM location, water depth, and lithology, have provided bounds on reasonable values of leak-off pressure, the minimum stress, and the matrix stress ratio. Contrary to the widely-used Eaton model, results from this study suggest that the locally-calibrated matrix stress ratio, K0, appears to be approximately constant as a function of depth. As a guideline for deriving facture gradients in an area of poor calibration, we would recommend a minimum stress fracture gradient method (e.g., Matthews and Kelly method), using a value of K0 of 0.8 in areas not affected by salt and a value of K0 of 0.95–1.0 for areas near to salt. Recommendations for conducting leak-off tests and interpreting LOT for leak-off pressure and minimum stress are included.

SESSION 15 — NUMERICAL MODELING--FRACTURES

ARMA 10-400

A New Approach to Hydraulic Fracturing Modeling in Naturally Fractured Reservoirs

Branko Damjanac, Ivan Gil, Matt Pierce, And Marisela Sanchez
Itasca International, Minneapolis, Minnesota, USA

Andre Van As
Rio Tinto Copper Projects, Brisbane, Australia

John Mclennan
University Of Utah, Salt Lake City, Utah, Usa

ABSTRACT
A typical hydraulic fracturing operation in a naturally fractured rock was simulated by using the Discrete Element Method, DEM (Cundall and Strack, 1979). In this model, a field-derived Discrete Fracture Network (DFN) was superimposed on an intact rock particle model to create a Synthetic Rock Mass (SRM). This SRM resembled both the mechanical (Pierce et al., 2007) and hydraulic (Hazzard et al., 2002) behavior of a specific naturally fractured rock mass. Fluid injection was simulated with this calibrated model to determine the geometry and orientation of the induced hydraulic fracture(s); also, the interaction between the pre-existing natural fracture network and the hydraulically induced fracture(s) was studied.

ARMA 10-322

Pore Distribution and Statistical Size Effect: a Discrete Element Analysis

Gharahbagh, A. E.
Department of Mineral Engineering, New Mexico Tech, Socorro, NM, USA

Fakhimi, A.
Department of Mineral Engineering, New Mexico Tech, Socorro, NM, USA &
Department of Civil Engineering, University of Tarbiat Modarres, Tehran, Iran

ABSTRACT
Rock is a quasi-brittle material that contains many pores, micro-cracks and flaws that are randomly distributed within the material. These pores and micro-cracks can affect the crack initiation stress and the tensile strength as well as the compressive strength of the material. A simple model to capture the effect of these defects on tensile strength is the weakest link theory in which rock is considered as a chain under tension. The chain breaks in tension when the weakest link fails.

The Weibull distribution used in this study is based on this simple theory. The rock was modeled using a bonded particle system. Numerical specimens of different sizes were generated. Numerical uniaxial tensile tests were conducted on these specimens that had different macro-pore sizes and macro pore distributions in order to investigate whether Weibull model is capable of explaining the scatter of the data. It is shown that while Weibull distribution can capture the statistical size effect for the mean tensile strength values, it can not ideally explain the scatter of the data.

ARMA 10-388

A Numeric Simulation of Rock Avalanches using the Combined Finite-Discrete Element Method, FEMDEM

Xiang, J. Latham, J-P. and Harrison, J.
Imperial College London, London, the United Kingdom

Zhang, Z.Q.
Xi'an University of Technology, Xi'an, P. R. China

ABSTRACT

The danger of rock slope failure has been recognised for a long time and is a constant concern in earthquake prone regions and where valleys are over-steepened by rapid tectonic uplift. In this paper, the so called combined finite-discrete element, FEMDEM, method is employed to model a simple planar failure. FEMDEM [1] modelling technology combines the multi-body particle interaction and motion modelling (i.e. Discrete Element Model, DEM) with the ability to model internal deformation of arbitrary shape (Finite Element Model, FEM). In this paper, the failure of a simple planar block in a 50 m high slope is simulated using FEMDEM. The 285 m2 basal plane is at 45 degrees and the Coulomb friction coefficient is set at 0.95 to initiate instability. Internal deformation of the block during accelerated sliding causes crack initiation and propagation. Two simulations of the sliding of a perched rock block are presented, the only difference in conditions being two different intact tensile strengths, 1MPa and 5MPa. They show a wide size distribution of boulders in the run-out material for the stronger 5MPa rock which is not observed in our simulations using rock with tensile strengths of 1 MPa. The size distribution of fragments and kinetic energy, two important parameters, for example in mining and quarrying, are analysed in this paper.

ARMA 10-150

A Damage and Fracture Model for Jointed Rock Masses and Application in Stability Analysis on an Underground Cavern Group

Kui Zhou, Weishen Zhu, Qianbing Zhang, Qingsong Ma and Qingsong Zhang
Geotechnical & Structural Engineering Research Center, Shandong University, Jinan , PR China

ABSTRACT

Numerous hydropower stations are located in high mountain-canyon areas in southwestern China. A number of deeper cracking zones frequently appear in the side walls of the underground caverns in these hydropower stations. The related principles and methods in fracture and damage mechanics are applied to study this phenomenon. A damage constitutive model is initially put forward using geometry damage principles. In this model, the initial geometry damage of jointed rock masses can be considered, which involve the major influencing factors such as joint plane areas, directions, and so forth. This constitutive model is derived according to the equivalent strain hypothesis. A failure criterion for crack coalescence and a damage evolution equation are deduced considering secondary cracks using the principles of fracture mechanics. Then the above model and analysis methods are programmed. Eventually, this new damage constitutive model is utilized to study on the stability of a group of underground caverns at a hydropower station in Sichuan Province. The obtained splitting depths from this model are close to the in-situ monitored ones using the deformation-electric-resistance-rate technology monitoring method, which validate the effectiveness of this fracture-damage constitutive model.

ARMA 10-221

Analysis of Sand Production Processes at the Pore Scale Using the Discrete Element Method and Lattice Boltzman Procedures.

Raquel Quadros Velloso, Euripedes A. Vargas Jr., Armando Prestes
Dept. of Civil Engineering, Catholic University, Rio de Janeiro, Brazil

Clemente J. Gonçalves
Senior Engineer, Research Division (CENPES), Petrobras, Rio de Janeiro, Brazil.

ABSTRACT
It is believed that coupled fluid-mechanical-erosional phenomena associated to san production derived from microscale based mechanisms as the disaggregation of particles from the rock matrix and their transport through the pores are best described at the particle and pore level. The present work presents results obtained from a numerical simulation study of these phenomena at the pore scale level. This study was carried out by coupling the discrete element method for the analysis of the mechanical behavior of the rock and lattice-Boltzman method for the simulation of fluid flow at the pore level. Computer codes were written to simulate both processes using the procedures described. One objective of the work was an improvement in the knowledge of micromechanical processes leading to solids production. It is believed that such understanding will improve the constitutive relationships necessary for sand prediction and used in continuum based methods of prediction, more amenable for applications in real case situations. Rock properties and texture, boundary conditions (stresses and drawdown) in the disaggregation and particle transport were considered. Preliminary results of the DEM two phase LBM coupling are also presented. Advantages and limitations of this micromechanical approach are also discussed.

SESSION 16 — **DISCONTINUITIES I**

ARMA 10-141

Intrastratal and Suprastratal Deformation Associated with Collapsed-Paleocave Systems

Loucks, R. G.
Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, U.S.A.

ABSTRACT
Collapsed-paleocave systems are common megascale diagenetic features that develop in carbonate strata at major unconformities. These collapsed-cave systems, composed of numerous individual collapsed passages and chambers, affect not only the strata in which they developed, but also strata deposited above the unconformity. Intrastratal and suprastratal deformation or damage zones consist of breccias, fractures, faults, and folds. Structural features associated with intrastratal deformation are on the scale of tens to hundreds of meters that develop above and adjacent to the paleocaves. Suprastratal deformation can affect up to 1 kilometer of lithified strata above the unconformity. As seen from seismic data and outcrops, suprastratal sags are hundreds to thousands of meters across and contain reverse and normal faults. Strata tilt into the sags by as much as 20°. As the cave system below ceases to collapse, tilt of the above strata decreases and finally becomes horizontal over the filled-in sag. Suprastratal deformation can form at any time during burial and collapse of the paleocave system, and it may occur during several episodes.

ARMA 10-325

Using Empirical Trends in Fracture Size-Frequency Data to Constrain Subsurface Fracture Abundance

Hooker, J. N. and Laubach, S. E.
Fracture Research and Application Consortium, Bureau of Economic Geology, Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, USA

ABSTRACT
Quantifying fracture intensity in the subsurface by direct fracture sampling is difficult in low-strain fractured reservoirs because 1) fractures typically dip steeply, and 2) the spacing of fractures large enough to influence fluid flow is generally wider than the width of a wellbore. It is therefore rare that more than one or two large natural fractures are preserved in core, precluding attempts to quantify fracture spacing. Microfracture scaling is a method to extrapolate large-fracture spacing

using microscopic fractures, whose average spacings may be sufficiently small for quantitative spacing analysis using vertical core. In this study we test microscopic-fracture intensity measurements from one-dimensional scanlines on scanning electron microscope-based cathodoluminescence images against scanlines across macroscopic fractures from horizontal cores. The size distribution of our highest-quality dataset is well fit by a power-law equation whose exponent is -0.6, which is close to values for veins reported in the literature. Because this exponent's absolute value is less than 1, the abundance of microfractures does not increase dramatically over the observed fracture-size scales. Thus, in typical core-width scanlines from low fracture-strain reservoirs, fewer than twenty microfractures are typically sampled, and independent power-law scaling extrapolations are unreliable. However, applying the observed power-law exponent to limited size-frequency data by varying the power-law coefficient greatly improves large-fracture spacing predictions.

ARMA 10-203

Stability of Rock Blocks Subjected to High-Velocity Water Jet Impact

Asadollahi, P.
Gall Zeidler Consultants, LLC, Ashburn, Virginia, USA

Tonon, F.
The University of Texas, Austin, Texas, USA

ABSTRACT
Currently, there is no formulation for evaluating scour caused by general failure modes of rock blocks having general shapes and subject to general loading including water pressures, which may cause failure modes such as divergence and flutter. In this paper, the stability of single rock blocks in plunge pools is investigated. An approach is presented to estimate pressure forces generated in plunge pools due to high-velocity jet impacts. In addition, a failure criterion is introduced for jointed rock masses. Finally, this scour model is implemented in BS3D (Block Stability 3 Dimensions), and it is validated using the results of case histories and prototypes followed by an example demonstrating the ability of BS3D in capturing dynamic divergence and flutter.

ARMA 10-265

An Improved K-means Clustering Method for the Automatic Grouping of Discontinuity Sets

Wong, L.N.Y. and Liu, G.
Nanyang Technological University, Singapore

ABSTRACT
An improved K-means dynamic clustering method has been proposed in this paper for identifying and delineating group (sets) of discontinuity data. Although the number of the desired clusters has to be defined in advance and is somewhat subjective, this drawback can be overcome by an improved classical algorithm to refine the orientation of the initial cluster centers. An iterative and automatic procedure for the cluster center estimation is developed, which is called by the main program to alleviate the influence of initial cluster center over the results. Besides, we have suggested using the acute inclination angle between and discontinuity surfaces as a distance measurement. Since the method is fully automatic, it is not necessary to construct density contour plots and no free parameters are required to be optimized. The method can be easily implemented on the MATLAB platform and readily used in any stages of geological survey. A case study which demonstrates the effectiveness of the dynamic clustering method is presented in this paper.

ARMA 10-296

Techniques for Identification and Prediction of Mechanical Stratigraphy in Fractured Rock Masses

La Pointe, P. R.
Golder Associates Inc., Redmond, WA, USA

ABSTRACT
The ability to identify and predict mechanical stratigraphy from limited borehole data is a common challenge for developing models to support mining, hard-rock construction, and water resource and energy development. In hard rock, the

interplay of lithostratigraphy and the rock deformation history often gives rise to layer-bound fracture systems bounded by stratigraphic or other types of geological surfaces that form major pathways for fluid movement. Correctly indentifying significant fractured layers in the rock mass, their lateral persistence, and their potential vertical connectivity can greatly improve predictions of subsurface flow and transport. Fracture data for many site characterization projects relies upon core or fracture image logs acquired in boreholes, and so methods that can identify and quantify mechanical stratigraphy from this type of data are widely applicable. Experience in developing predictive fracture models for petroleum reservoirs and highlevel nuclear waste repositories have led to a technique for identifying and quantifying the facture intensity in mechanical layers called Cumulative Fracture Intensity (CFI) analysis. This technique requires only subsurface fracture data from core or fracture image log. The analysis makes it possible to identify mechanical stratigraphy with a high degree of precision, and assess its relation to depositional framework, bedding thickness, secondary fault zone development, rock mass mechanical properties and deformation history. illustrations of this method are presented, along with case histories to illustrate the application for site characterization and subsequent hydrogeomechanical modeling.

SESSION 17 — INJECTION AND DEPLETION

ARMA 10-123
Modeling of the Hydraulic Fractures in Unconsolidated Oil Sands Reservoir

Xu, B., and Yuan, Y.
BitCan Geoscience & Engineering Inc., Calgary, Alberta, Canada

Wong, R. C. K.
Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada

ABSTRACT
Some fundamental mechanisms of hydraulic fracturing in unconsolidated formations have not been well understood although they have been studied quite extensively for hard rock formations. Laboratory and field evidences demonstrated that during the hydraulic fracturing of the unconsolidated porous materials such as oil sands reservoirs in Alberta, Canada, a single planar fracture is unlikely to occur, and the outcome is a high-porosity zone permeated by a network of microcracks. Thus, the numerical approaches based on the conventional fracture mechanics have limitations in modeling such complex processes. The purpose of this paper is to present numerical simulation techniques in modeling the progressive mechanical breakdown of, and associated fluid flow in, unconsolidated oil sands. We will follow the continuum mechanics and use elasto-plastic model with strain softening for simulating the sands matrix deformation. The intimate coupling between the deformation and fluid flow is considered via a porosity-saturation-dependent isotropic permeability model. All such theoretical approaches are tested by history matching of mini-frac tests in the oilsands reservoirs.

ARMA 10-231
Finite Element Modeling of Rock Cutting

Jaime, M.C.[2], Gamwo, I.K.[1], Lyons, D.K.[1], and Lin, J.S.[1,2]
[1] U.S. Department of Energy, National Energy Technology Laboratory, Pittsburgh

[2] University of Pittsburgh, Pittsburgh

ABSTRACT
Rock cutting by an advancing drilling Polycrystalline Diamond Compact cutter poses a serious challenge from a modeling perspective. This is especially true with finite element analysis. In this study, the explicit finite element code LS-DYNA was employed. The study first looked into the merits and shortcomings of various approaches ranging from the Eulerian and ALE formulation, to the Lagrange formulation, with only the last one to be suitable for the present study. These different numerical approaches are evaluated in terms of their ability to give reasonable cutting forces, and the resolution and extent of the fragmentation process captured. The basic rock cutting model investigated was fashioned after the laboratory linear rock scratching test. This study has successfully modeled the various fracture phases of the fragmentation in rock cutting, from crack initiation, chip formation, and to the interactions of chips, cutter, and the rock sample. The magnitudes of cutting forces obtained were also consistent with laboratory tests.

ARMA 10- 139

Injectivity and Fracturing in Unconsolidated Sand Reservoirs: Waterflooding Case Study, Offshore Nigeria

Khodaverdian, M., Sorop, T.G. and Van den Hoek, P.J.
Shell International Exploration and Production, Rijswijk, The Netherlands

Sathyamoorthy, S. and Okoh, E.
Shell Nigeria Exploration and Production Company Ltd, Lagos, Nigeria

ABSTRACT
Water flooding is performed in unconsolidated sand reservoirs for pressure support, improved oil recovery, or for produced water disposal. Injection in these formations leads to "fracture" propagation due to formation plugging by solid impurities in water, even in multi-Darcy sand. This paper addresses the questions of soft sand injectivity and fracturing in the context of a study carried out for a particular field in offshore Nigeria. Water flooding has been performed in this field since late 2005 for pressure support and productivity improvement. Through the analyses of pressure falloff (PFO) data from a number of injectors we have established that indeed long "fractures", in the order of 10's or possibly over 100 meters, could be induced in the multi-Darcy sand. These conclusions have been verified through injectivity analyses and fracture propagation modeling. Nevertheless, the available data suggest that for some wells sand production, wellbore fill and near-wellbore plugging contribute to severe injectivity decline.

ARMA 10-318

Hydraulic Fracture Propagation in Pre-Fractured Natural Rocks

Meng, C
Delft University of technology, Delft, the Netherlands

Pater, C.J. de
StrataGen Delft, Delft, the Netherlands

ABSTRACT
We conducted a series of hydraulic fracture initiation tests with pre-fractured natural rock samples. The objective is to characterize the interaction between hydraulic fracture initiation and natural fracture infiltration and opening. The natural fracture was made by cleaving a rock cube into two or three layers and putting the parts back together. The hydraulic fracture is initiated by pressurizing the borehole drilled perpendicular to the layers. The rock types include Colton Sandstone, Felser Sandstone and Pierre Bleue Limestone. Test parameters include confining stress and fluid viscosity. Injection fluids include silicon oil and cross-linked gel. A model was built to simulate the scenario that a hydraulic fracture interacts with a natural fracture. When the hydraulic fracture and the natural fracture interface intersect, the model examines whether the fracture initiation criterion is met for the intact side of the media. The hydraulic fracture can then either step over the natural fracture and propagate into the intact solid or stop at the intersection edge. In this paper, we first introduce the experimental setup and the mechanisms of the fracture propagation across discontinuities. Based on the concepts formulated, we introduce the numerical approach and discuss the modeling results against experimental results. From the tests and modeling we conclude that whether a hydraulic fracture can cross-over a natural fracture depends on the confining stress, injection fluid properties, fracture initiation location and interface coupling of the natural fracture.

ARMA 10 - 304

Stress Evolution due to Depletion in an Ellipsoidal Elasto-Plastic Reservoir

Dunayevsky, V.A.n Myers, M. T. and Bennett, M.W.
Shell International E&P, Houston, Texas, USA

ABSTRACT
The Eshelby like approach has been used to successfully model the stress, strain and displacement fields associated with a depleting reservoir. A modified Cam-Clay material model was implemented for the constitutive equations for the reservoir material. The exterior of the reservoir is modeled as an infinite homogeneous linear elastic material. Body forces are not

considered. These assumptions allow an semi-analytical approach to be applied. Applications of this approach include "quick look" solutions for well failure estimates, evaluating time-lapse seismic candidates, effects of reservoir tilting, CO2 sequestration, estimates of fault activation etc. Here we discuss the use of the model to investigate how the external stress field of a depleting reservoir effects fault activation exterior to the reservoir. This is accomplished by running the model to determine the stress and strain fields induced in the elastic host by the depleting reservoir. The fault is then represented as an elastic-plastic (modified Cam-Clay) ellipsoidal inclusion imbedded in the host stress field calculated in the first step. Three mechanisms are discussed as criteria for fault activation. Runaway instability and negative rate of plastic work are criteria for determining when the material significantly weakens. Runaway instability is equivalent to the scenario when uncontrollably growing strains develop inside the fault. Negative rate of plastic work represents the case when the model predicts that the fault delaminates from the host material. Strain localization is beyond the scope of this paper and will be addressed in a later paper. The criteria for fault reactivation is sensitive to fault, reservoir, and host material properties and their contrast. The orientation and spacing of the reservoir and fault and their impact on fault reactivation are explored and found to be critical. However, the aspect ratio of the fault is not a critical parameter. This approach deviates significantly from traditional methods of estimating fault activation, which ignore fault orientation. The external stress and strain are equated in these models, which is not true, particularly for sharp material contrasts between the host and fault. The modified Cam-Clay model is also used for the fault material model.

SESSION 18 — NUMERICAL MODELING - PETROLEUM GEOMECHANICS

ARMA 10-106

On the Importance and Computation of Cohesive Force Contribution to the Total Potential Energy in 3D-DDA

Keneti, S. A. R.
Department of Civil Engineering, Schulich School of Engineering, University of Calgary, Calgary, Alberta, Canada

Jafari, A.
Department of Mining Engineering, Pardis Engineering Faculties, University of Tehran, Tehran, Iran

ABSTRACT
An essential part of three dimensional Discontinuous Deformation Analysis, 3D-DDA, is a rigorous contact theory governing the interaction of the blocks. In this theory the type of contact is important because it determines the mechanical response of the blocks in contact. The Main Plane (MP) method for contact detection is capable to compute all contact patterns during DDA computational process. In this method, in addition to its similarity to the existing methods in converting all contact types into a simple "vertex to face" contact pattern to enhance computation efficiency, each contact type can also be treated according to its individual behavior. The "face to face" contact pattern is one of the most common modes of contact between two neighboring blocks in 3D state. Computation of the contact area between two blocks that are in "face to face" contact is useful and is necessary to compute the contribution of the joint cohesion to the shear resistance along contacting block surfaces. The prevailing model of joint shear resistance seems to be purely frictional, so the effect of joint cohesion may not be significant; however, the capability of considering joint cohesion in 3D DDA should still be a useful extension, especially for slope stability analysis. In this paper the importance of common area and the ability of MP method to do so were highlighted first. Then, using the "Simplex Integration" technique, a straightforward procedure was introduced for continuously computing and updating this overlapped area while blocks slide on each other. This method was then verified by solving a simple problem of sliding of two blocks in contact, which is, however, similar in computation process to more complicated sliding problems. In this paper the energy function of cohesive force and its contribution to the total potential energy in 3D-DDA was also derived which could be used in future works in DDA together with the developed method of computing the contact area.

ARMA 10-523

Three-Dimensional Fracture Simulation using the Virtual Multidimensional Internal Bond

Zhang, Z.Z., and Ghassemi, A.A.
Harold Vance Department of Petroleum Engineering, Texas A&M University

ABSTRACT
Fracture propagation, especially for fractures embedded in the body, simultaneously involves Mode I, Mode II and Mode III fracture pattern. Therefore, a two-dimensional simulation has limited applicability in modeling realistic fracture behavior, and a 3D propagation model is necessary. In this paper we present a VMIB model for simulating 3D fracture propagation. Fracture behavior is naturally three-dimensional, involving macro fracture initiation and propagation rooted in bond rupture at the micro scale. The virtual multidimensional internal bond (VMIB) model bridges the processes of macro fracture and micro bond rupture. The macro three-dimensional constitutive relation in VMIB is derived from the one-dimensional bond in the micro scale and is implemented in a 3D finite element method. To represent the contact and friction between fracture faces, the three-dimensional element partition method is employed. The model is applied to simulate fracture propagation and coalescence in typical laboratory experiments, and to analyze the propagation on an embedded fracture. Numerical simulations show good agreement with experimental observations.

ARMA 10-131

Numerical Determination of Representative Volume Element of Rock

Gharahbagh, A. E.
Department of Mineral Engineering, New Mexico Tech, Socorro, NM, USA

Fakhimi, A.
Department of Mineral Engineering, New Mexico Tech, Socorro, NM, USA &
Department of Civil Engineering, University of Tarbiat Modarres, Tehran, Iran

ABSTRACT
The concept of Representative Volume Element (RVE) of simulated rock with different pore size and pore distribution is studied in this paper. A total of 500 numerical specimens with porosities in the range of 16% to 17% and with different macro-void size and macro-void distribution were generated. The rock is modeled using a bonded particle system. Numerical uniaxial compressive tests were conducted on these specimens in order to investigate the size of the representative volume element corresponding to different mechanical properties of rock. It is shown that the scatter of the data reduces by increasing the sample size. The scatter of the engineering properties studied in this paper (uniaxial compressive strength, Young's modulus, Poisson's ratio, and crack initiation stress) is greater for samples with larger macro-void size compared to that of samples with smaller macro-pore size. The results of this study suggest that the size of the RVE is not a unique property and depends on the chosen parameter of interest.

ARMA 10-389

Development of Virtual Geoscience Simulation Tools, Vgest for Irregular Blocky Rock Applications in Rock Engineering using the Combined Finite Discrete Element Method, Femdem

Latham, J.-P. Xiang, J. and Harrison, J.P.
Department of Earth Science and Engineering, Imperial College London, UK

Munjiza, A.
Department of Engineering, Queen Mary College London, UK

ABSTRACT
The complexity of geological materials makes it a huge challenge to simulate geo-engineering processes reliably. Powerful simulation tools that manage to handle their discontinuous nature are rare. Most are proprietary software where the black-box workings and major investment needed can be a block to researchers and teachers. VGeST is a suite of freely available Open Source simulation tools based on probably the most powerful discontinuum modelling approach, i.e. FEMDEM, that can easily take advantage of the versatile graphical user interface (GUI) functionality of leading, yet affordable proprietary pre-processing. The user effort in building input files for the 2D and 3D FEMDEM solvers is minimized through interactively completing drop-down templates and use of meshing tools in the pre-processor. In this paper we provide an overview of the motivation for VGeST, a taste of the working environment of VGeST, and an illustration of the power of codes Y2D and Y3D to tackle stresses and displacements in blocky or layered systems as well as problems of a granular nature which benefit from VGeST's inclusion of a shape library of virtual particles, P3D.

ARMA 10-459

A Confinement and Deformation Dependent Dilation Angle Model for Rocks

Cai, M
School of Engineering, Laurentian University, Sudbury, Ontario, Canada

Zhao, X.G.
Beijing Research Institute of Uranium Geology, Beijing, China

ABSTRACT
A mobilized dilation angle model considering the influence of both confining stress and plastic shear strain is proposed in this paper. The model is used to predict the volumetric-axial strain relationships of a few rock samples and the results are found to be in good agreement with experimental results. Realistic post failure dilation behaviour of rocks can be captured using induced displacement around tunnels located in different rock masses. It is illustrated from a few examples that displacement distributions obtained from the dilation angle model are more reasonable, when compared with the general trend measured underground

SESSION 19 — DISCONTINUITIES II

ARMA 10-506

3D Poroelastic Analysis of Rock Failure around a Hydraulic Fracture

Ghassemi, A. Zhou, X.X., and Rawal, C.
Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, TX, U.S.A

ABSTRACT
Three-dimensional stress and pore pressure distributions around a hydraulic fracture are numerically calculated to analyze the potential for formation failure resulting from pressurization of the hydraulic fracture. The three-dimensional numerical model used combines the finite element method and the poroelastic displacement discontinuity method. Elements of the model formulation and solution procedures are first presented. Then, the problem of constant water injection into a rectangular fracture in Barnett shale is presented. Using the Mohr Coulomb failure criterion with a tension cut-off, results show that rock failure can occur in the vicinity of the fracture, especially near the fracture tips. The dominant failure mode is tension in the close vicinity of the fracture where the pore pressure attains its highest values. Shear failure potential exists away from the fracture walls where shear stresses are sufficiently high for the relatively weak rock. The extent of the potential failure zone increases with increasing injection rate.

ARMA 10-155

Modeling of Near-Surface Bowl-Shaped Fractures

Gordeliy, E.
University of Minnesota, USA

Detournay, E.
University of Minnesota, USA & CSIRO Earth Science and Resource Engineering, Australia

Napier, J.A.L.
University of the Witwatersrand and CSIR, South Africa

ABSTRACT
This paper aims to quantify, through numerical simulations, the geometry of an axisymmetric sub-surface crack subject to a uniform pressure simulating fluid or gas pressure. Two algorithms based on the displacement discontinuity method are employed: one that relies on symmetry, as the fracture is discretized into ring elements, and another one in which the fracture surface is represented by flat, triangular elements. The fracture propagation is modeled by adding new elements to the existing fracture, with the inclination of a new element determined from the maximum tensile stress criterion. The numerical results are compared with available results of simulations of bowl-shaped fractures and laboratory experiments.

ARMA 10-390

Stress Heterogeneity in a Fractured Rock Mass Modelled with the Combined Finite-Discrete Element Method

Harrison, J.P., Xiang, J. and Latham, J.-P.
Imperial College, London, UK

ABSTRACT
Although it has long been recognised that fractures in rock perturb the local stress field, it has been difficult to both simulate and visualise the stress heterogeneity developed in highly fractured systems. Here, we use the open source 3D FEM-DEM code Y3D, part of the Virtual Geoscience Simulation Tools (VGeST) suite, to model a discontinuous rock mass and hence rigorously determine the complete state of stress within it. The model replicates a 200 m cube dissected by two discontinuity sets, the properties of which are purely frictional. The results show that a significant degree of stress heterogeneity is induced. This heterogeneity is seen in both the orientation and magnitude of the principal stress components, and is largely independent of the frictional properties of the discontinuities. Although this is only a preliminary report of work in progress, it nevertheless suggests that it is important to understand the geological structure at a stress measurement location, and that identifying the in situ stress state in a discontinuous rock mass from a few stress measurements may be very difficult.

ARMA 10- 336

Limits of Applicability of the Finite Element Explicit Joint Model in the Analysis of Jointed Rock Problems

Riahi, A. & Hammah, E.R.
Rocscience Inc., Toronto, ON, Canada

Curran, J.H.
Civil Engineering Department, University of Toronto, Toronto, ON, Canada & Rocscience Inc.

ABSTRACT
This paper compares the governing equations and kinematics of joint elements used in continuum numerical methods to those of contact enforcement methods used in discrete element techniques. It provides guidelines for choosing between discontinuous techniques (namely, the distinct element method and the discontinuous deformation analysis) and continuum techniques (such as the finite element method) with joint elements in the analysis of problems with pre-existing discrete fractures.

ARMA 10-154

Crack Localization and Characterization in Solid Media using Time Reversal Techniques

Anderson, B. E.
Acoustics Research Group, Dept. of Physics & Astronomy, Brigham Young Univ., Provo, Utah, USA

Griffa, M.
Lab for Building Sci. & Tech., EMPA, Swiss Federal Lab. for Materials Testing and Res., Dübendorf, Switzerland

Ulrich, T.J., Le Bas, P.-Y., Guyer, R. A., and Johnson, P. A.
Geophysics Group EES-17, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

ABSTRACT
Time Reversal (TR) is a technique that, among other things, allows one to locate a source of wave energy at an unknown position. Cracks are sources of nonlinear harmonic-frequency content when they are dynamically excited. Thus TR may be used to locate cracks since they are sources of the nonlinear frequency content. This paper will describe experiments, conducted over the past several years, to locate surficial cracks, near surficial cracks, and finally buried cracks. Finally, a means of characterizing a crack (e.g. its orientation) will be discussed. The ability to locate and characterize cracks may lead to better design of mechanical parts and may be used to monitor the structural health of solid samples, potentially including rock formations.

SESSION 20 — GEOPHYSICS AND MONITORING: ACOUSTICS AND TOMOGRAPHY

ARMA 10-297

A New Model for Long-Distance Movement of Earthquake Induced Landslide

Chen, G.
Kyushu University, Fukuoka, Japan & Visiting Prof. of Institute of Earthquake Science, China

Zen, K. and Zheng, L.
Dept. of Civil and Structural Engineering, Kyushu University, Fukuoka, Japan

Jiang, Z.
Institute of Earthquake Science, China Earthquake Administration, China

ABSTRACT
A new model called Multiplex Acceleration Model (MAM) is presented for understanding the mechanism of long run-out distance of an earthquake induced landslide. The collision behavior between a falling stone and the slope is analyzed by both theoretical and numerical methods. The effect of earthquake on the run-out distance is investigated by shaking table tests. The landslide induced by the 2008 Wenchuan Earthquake in Donghekou is simulated by numerical method DDA.

ARMA 10-491

Split Hopkinson Resonant Bar Test and its Application for Seismic Property Characterization of Geological Media

Nakagawa, S. and Kneafsey, T.
Lawrence Berkeley National Laboratory, Berkeley, California, USA

ABSTRACT
Conventional resonant bar tests allow measuring seismic properties of rocks and sediments at low frequencies (several kilohertz). However, the tests require a long, slender sample which is often difficult to obtain from the deep subsurface and weak and fractured formations. In this paper we present an alternative low-frequency measurement technique to the conventional resonant bar tests. This technique involves a jacketed core sample mediating a pair of long, metal extension rods with attached seismic source and receiver—the same geometry as the split Hopkinson pressure bar test for large-strain, dynamic impact experiments. Because of the added length and mass to the sample, the resonance frequency of the entire system can be lowered significantly, compared to the sample alone. The proposed "Split Hopkinson Resonant Bar (SHRB)" test is applied in two steps. In the first step, extension and torsion-mode resonance frequencies and attenuation of the system are measured. Then, numerical inversions for the compressional and shear wave velocities and attenuation are performed. We applied the SHRB test to synthetic materials (plastics) for testing its accuracy, then used it for measuring the seismic velocities and attenuation of a rock core containing supercritical CO2 and a sediment core during formation of methane hydrate within.

ARMA 10-504

Seismic Wavespeed used to Approximate Rock Mass Quality in Unweathered Sandstone

Putnam, N. H.
Missouri University of Science & Technology, Rolla, MO, USA

Reppert, P.M.
Massachusetts Institute of Technology, Cambridge, MA, USA

Blouin S. E. and D. E. Chitty
Applied Research Associates, Alexandria, VA, USA

ABSTRACT
The influence of joint spacing on seismic cross-hole wavespeed was measured in unweathered sandstone in order to develop correlations between rock mass quality and in situ modulus. Cross-hole seismic wavespeed were determined in three study areas with closely, moderately and widely spaced joints, using a 'seismic while drilling' technique described in another paper [1]. Wavespeed profiles were measured perpendicular and parallel to the jointing within each study area. In situ wavespeeds were normalized by dividing by the ultrasonic wavespeeds from intact core to provide a ratio of in situ wavespeed to intact wavespeed as a function of joint spacing. These ratios can serve as a direct measure of rock mass quality. They can also be used to compute in situ modulus. The wavespeed ratio was compared to the Rock Mass Rating 89 (RMR) [2]. The wavespeed ratio appears to offer a direct measure of rock mass quality that can be obtained efficiently using a compact combination rotary percussion drilling and coring rig.

ARMA 10-330

The Reflectivity and Transmissivity of Anisotropic Materials: A Physical Modeling Study

Ortiz-Osornio, M., & Schmitt, D.R.
Institute for Geophysical Research, University of Alberta, Edmonton, AB, Canada

ABSTRACT
In this paper we measure the reflected and transmitted waveforms from a liquid-anisotropic solid interface for two different materials. The first one, considered low attenuating, is a quartz crystal with trigonal symmetry; the second one, considered highly attenuating is a Phenolic CE material expected to be weakly orthorhombic. Reflectivity of the quartz crystal shows that the Schoch shift, observed in isotropic materials, is duplicated. This duplication of the Schoch shift depends on the azimuth and, can be used to identify principal planes of symmetry. Effects of tilting are studied with the Phenolic material for tilts of 0°, 30° and 90°. Our results show that, although difficult, tilting variations can be estimated mean azimuthal analysis of the reflectivity with the angle of incidence. However, the most important feature is variation of the critical angle, which increases with tilting. From the transmissivity tests, we also observed that the velocities of the two quasi-S waves are more affected by the tilt than the velocities of the quasi-P.

ARMA 10-461

Woodford Shale Mechanical Properties and the Impacts of Lithofacies

Sierra, R.
The PoroMechanics Institute/ Reservoir Characterization Institute, The University of Oklahoma, Norman, Oklahoma, U.S.A

Tran, M.H. and Abousleiman, Y.N.
The PoroMechanics Institute, The University of Oklahoma, Norman, Oklahoma, U.S.A

Slatt, R.M.
Reservoir Characterization Institute, The University of Oklahoma, Norman, Oklahoma, U.S.A

ABSTRACT
In this paper, preserved Woodford Shale samples of different mineralogy compositions were obtained from a shallow research well in Oklahoma and prepared for various laboratory mechanical characterizations including the Ultrasonic Pulse Velocity (UPV) measurements, the Brazilian Tensile tests, and the Chevron Notched Semicircular Bend (CNSCB) tests with acoustic emissions (AE) recorded during the fracturing process to monitor the fracture initiation. The UPV and Brazilian test results show a clear anisotropic nature of Woodford Shale poroelastic properties and tensile strength. Investigations on the effects of shale mineralogy and morphology on its anisotropic mechanical properties show correlation between the degrees of anisotropy with clay packing density. Despite the reported results of the limited number of tests, an increasing trend of Woodford Shale tensile strength with carbonate content could be observed. This proportional increase of tensile strength with carbonate content may suggest the precipitation nature of carbonate minerals in Woodford Shale in addition to the detrital carbonate shell fragments as observed with thin sections analysis. Finally, CNSCB test results showed that the fracture toughness of the lower clay Upper Woodford samples is significantly higher (up to 57%) than the fracture toughness of samples from the more clay rich Middle and Lower Woodford. Also, the acoustic emissions prior to the uncontrollable fracture growth under CNSCB tests could only be observed for the lower clay samples belonging to the Upper Woodford.

SESSION 21 — COUPLED PROCESSES II

ARMA 10-342

Reservoir Depletion Effect on In-Situ Stresses and Mud Weight Selection

Fanhong (Frank) Meng & Giin-Fa Fuh
ConocoPhillips, Houston, Texas, USA

ABSTRACT
Reservoir depletion will cause in-situ stress reductions in both reservoir and overburden (caprock) sections. Horizontal and vertical stresses will also be affected by the depletion. Mud weights must be adjusted or a casing string must be set before drilling through depleted reservoirs. This paper shows the evaluation of reservoir depletion effects on wellbore stability for a North Sea field. The analysis is conducted based on drilling and log-derived in-situ stresses, well core testing data, formation properties, well trajectory information and reservoir depletion induced stress changes. A geomechanical model was verified with field history cases, and used to predict the stability for a proposed well under depletion conditions. In the analysis, the stress reductions due to reservoir production will be discussed. Reservoir pressures depleted from 1.8 s.g. (15.0 ppg) to 0.6 s.g. (5.0 ppg). In the depletion case, the in-situ stresses were re-calculated and MW was analyzed. Recommendations and conclusions were given for drilling through the reservoir and overburden sections. Actual drilling results strongly supported the conclusions and suggestions from the evaluation.

ARMA 10-241

Evaluation of Validity of Cubic Law and Hydro-Mechanical Properties of Rock Fracture using Coupled Shear-Flow Tests and 3-D Numerical Simulation

Li, B., Jiang, Y., Yang, L. and Tanabashi, Y.
Faculty of Engineering, Nagasaki University, Nagasaki city 852-8521, Japan

Xiong, X.
State Key Laboratory of Hydro Science and Engineering, Tsinghua University, Beijing 100084, China

ABSTRACT
A great number of experimental investigations and numerical simulations have been performed in the past, regarding coupled shear-flow behavior of rock fractures. However, some of the key issues such as shear-induced complexity of void geometry during large shear displacements remain unresolved. In this study, coupled shear-flow test was conducted on an artificial rock specimen with natural rock fracture characteristics. 3-D numerical simulation was then used to simulate the fluid flow through the rock fracture with void geometry obtained from test. The results show that transmissivity of fracture increases during shear process due mainly to the dilation of fracture, and the total process exhibits a two-stage behavior in terms of the change character of transmissivity and contact area distribution. The transmissivity also varies with water head in terms that transmissivity decreases with the increase of water head. The contact ratio and distribution as well as the surface roughness have large effect on the transmissivity. The numerical simulation by solving 3-D Navier-Stokes equations provides more precise predictions to the flow behaviors than some simplified models neglecting nonlinearity of fluid flow.

ARMA 10-245

Relations between Coal Permeability and Directional Strains and their Application to San Juan Basin

Zhongwei Chen, Jishan Liu
School of Mechanical Engineering, The University of Western Australia, WA, Australia

Zhejun Pan, Luke Connell
CSIRO Earth Science and Resource Engineering, Private Bag 10, Clayton South, Victoria, Australia

Derek Elsworth
Department of Energy and Mineral Engineering, Pennsylvania State University, PA, USA

ABSTRACT
In this study a permeability model is developed to define the evolution of gas sorption-induced permeability anisotropy under the full spectrum of mechanical conditions spanning prescribed in-situ stresses through constrained displacement. In the model, gas sorption-induced coal directional permeabilities are linked into directional strains through an elastic modulus reduction ratio, Rm. This defines the ratio of coal mass elastic modulus to coal matrix modulus (0<Rm<1) and represents the partitioning of total strain for an equivalent porous coal medium between the fracture system and the matrix. Where bulk coal permeability is dominated by the cleat system, the portioned fracture strains may be used to define the evolution of the fracture permeability, and hence the response of the bulk aggregate. The coal modulus reduction ratio provides a straightforward index to link anisotropy in deformability characteristics to the evolution of directional permeabilities. The validity of the model is evaluated against results for special cases representing uniaxial swelling, constant volume reservoirs, and for the case of ten coalbed methane production wells in San Juan Basin.

ARMA 10-152

Analysis of Fracture Mechanical Behavior under Normal Stress

Jocker, J. and Prioul, R.
Schlumberger-Doll Research, Cambridge, MA, USA

ABSTRACT
The mechanical and hydraulic properties of subsurface fractures are of importance to many aspects of hydrocarbon reservoir production, characterization, and management. The specific normal stiffness is a fracture mechanical property that may be inferred from sonic and seismic data. The specific stiffness has units Pascal per meter, and as such it is a property very different from conventional stiffness, which has Pascal units. By representing a fracture as a thin "equivalent" layer, we explore the implications of this difference in the framework of elastic wave propagation in the presence of fractures. Through the analysis of three previously published datasets, it is demonstrated that fractures are orders of magnitude more compliant than the medium which contains them. We apply the equivalent layer model to arrive at relaxed state fracture apertures which are in excellent agreement with values found through a completely independent approach. The fracture with the smallest specific stiffness is demonstrated to also have the largest stiffness of the set of three, thus demonstrating the ambiguity involved when interpreting values for specific stiffness. Because specific stiffness is defined as the ratio of stiffness to aperture, it is not a useful parameter from which to infer hydraulic properties.

ARMA 218

Analytical and Numerical Analysis of Fluid Flow Through Rough Natural Fracture Profiles

Hosseinian, A., Rasouli,V. and Bahrami, H.
Petroleum Engineering Department, Curtin University of Technology, Perth,WA, Australia

ABSTRACT
The complexity of fluid flow modeling through a single rough walled fracture is due to its tortuous paths followed by the fluid particles and presence of uneven walls. Flow of fluid can take place through a single fracture, fault, or a network of fractures. Large body of numerical and simple analytical solutions has been proposed to study the fluid flow in a single fracture. The main difficulty in all these models is how appropriately incorporating the effect of fracture morphology, which has a significant influence on fluid flow behavior. Pressure drop and velocity magnitudes of synthetic and real rock profiles were estimated using FLUENT software. Pressure drop showed a good correlation with a new surface roughness parameter (DR1) already developed based on the amount of dispersion for distribution of normal vectors to a surface. The results indicated that the larger is profile's DR1 (i.e. rougher profile) the higher would be pressure drop along the fracture. However, it was demonstrated that the existence of extremely reduced size openings against fluid path could be more influencing on flow behavior than fracture geometry.

TUESDAY FLOOR PRESENTATIONS

ARMA 10-125

Study of Characteristics of an Excavation Damaged Zone around Deeply Buried Tunnels under Blasting Conditions

Yan, P., Shan, Z.G, Chen, X.R., Zhou, Y.
Hydro China Huadong Engineering Corporation, Hangzhou, Zhejiang, China

ABSTRACT
Characteristics of the Excavation Damaged Zone (EDZ) have important significance on surrounding rock stability assessment and support design. Through detecting and analysis of the EDZ of Jin-ping Access Tunnel with a general depth 1500m~2000m, the influence of blasting load, in-situ stress transient unloading and static stress redistribution on EDZ were studied and compared. The damage mechanism of in-situ stress transient unloading to rock mass was also studied adopting numerical simulation technique. The result indicates that the extent of EDZ is significantly influenced by the state of in-situ stress, and the EDZ of Jin-ping Assistant Tunnel could be divided into two parts: Inner Damage Zone (IDZ) and Outer Damage Zone (ODZ). The IDZ is attributed to blasting load and transient unloading of in-situ stress, and is characterized by a more rapid reduction of acoustic velocity of rock mass, while the ODZ is caused by redistribution of insitu stress and characterized by a gradual reduction of acoustic velocity. In addition, the extent of IDZ is significantly lager than that of ODZ, and its distribution on tunnel section is strongly controlled by the redistribution stress field after excavation, which indicates that the effect of in-situ stress transient unloading during blasting is one of the causes of IDZ, and it is confirmed by both detecting results and theoretical analysis in this paper.

KEY WORDS: Deep tunnel; Excavation damage zone; Acoustic detecting; d unloading; In-situ stress

ARMA 10-127

Behavior of Marble at Jinping II Project--Part 2: Rockmass

Zhang, C.S, Chen, X.R, Chu,W.J
Hydro China Huadong Engineering Corporation, Hangzhou, Zhejiang, China

Zhu, Y. S and Zhu, H.C.
Itasca Consulting China Ltd., Wuhan, Hubei, China

ABSTRACT
Part 2 of the paper focuses on the description of fracturing and post-peak behaviors of the rock masses of different qualities. For the good quality rockmass with GSI value over 70, the attempt was made to determine the HB parameters in order to use tranditional continuum numerical codes such as FLAC3D and 3DEC. However, for the rockmass with GSI in the range between 50 and 70, it has been found that discontinuum methods would have to be used due to the significant fracturing behavior. At the depth of 1,800m from the ground surface at the Jinping II Project, fracturing becomes a dominated ground response while advancing the tunnel in the rockmass with GSI value around 55. The tranditional continuum methods with HB constitutive law seem unable to explain such response. The discontinuum code of PFC and UDEC was thus employed to describe the fracturing-dominated behavior. As the discontinuum approach describes the rockmass behavior at micro-scale and thus is essential, the residual strength envelops are achieved with this approach for the rockmasses with different GSI values in discussion. Comparing to the peak strength envelops, the residual srength envelops also show a behavior with increasing mb but descreasing σcr when using HB criterion, and a cohension-weakening but friction-strengthening hehaviour when using conventional Mohr-Columb criterion.

ARMA 10-144

Geotechnical Safety Program for Underground Storage Caverns in Salt

Zhang, Lianyang
University of Arizona, Tucson, Arizona, USA

Ralph, Grismala
ICF International, Lexington, Massachusetts, USA

Silva, Francisco.
Geotechnical Consultant, Lexington, Massachusetts, USA

ABSTRACT
Considering the large volume and different types of material stored in salt caverns, it is important to ensure that the salt cavern be designed, constructed and operated safely. Since salt caverns are constructed in a geological formation, the structural safety problem of a salt cavern is essentially a geotechnical problem. In this paper, we describe the application of the Geotechnical Safety Program (GSP) to a gas storage cavern in salt, focusing on the first two components – performance criteria and design assessment. To develop the performance criteria, we considered performance aspects in different categories. For each performance aspect, we developed the performance criteria by determining the consequences of failure, selecting a tolerable level of risk, establishing criteria of performance, and ensuring that the criteria meet appropriate legal requirements and accepted standards of practice. The design assessment was conducted by checking the design conditions, identifying the critical mechanisms of performance, identifying typical and critical sections, reviewing the field and laboratory data, identifying major uncertainties and critical aspects of performance, and recommending actions to improve safety. Based on the design assessment, we identified several performance aspects which do not meet the performance criteria and recommended changes and/or measures so that the performance criteria can be met.

ARMA 10-171

Inverting for Creep Strain Parameters of Uncemented Reservoir Sands using Arbitrary Stress-Strain Data

Hagin, P.N.
Chevron ETC, San Ramon, California, USA

Zoback, M.D.
Stanford University, Stanford, California, USA

ABSTRACT
Creep strain experiments on uncemented reservoir sands suggest that the time-dependent component of deformation can be modeled using linear viscoelasticity theory. The standard approach to solving for the values of the appropriate model parameters is to fit creep strain data as a function of time. However, by writing the creep compliance function in terms of strain-rate rather than strain, it is possible to solve for the values of the model parameters using arbitrary time-histories of stress-strain data. Rewriting the creep compliance function as the conjugate stress relaxation function allows constant loading-rate or step-hold loading data to be used to constrain the model. Complex loading histories can be divided into branches of approximately constant stress- or strain-rate and solved piecewise. After deriving the necessary equations, we show that the method successfully reproduces the known creep compliance function of an example uncemented reservoir sand.

ARMA 10-188

Field Test Study on the Reflection Laws of Seismic Waves on the Large-Scale Underground Water-Bearing Body

Xiao Zhang, Shucai Li, Qingsong Zhang and Rentai Liu
Geotechnical and Structural Engineering Research Center, Shandong University, Jinan, P.R. China

Ning Zhang
Institute of Hydroelectric and Geotechnical Eng., North China Electric Power Univ, Beijing China

ABSTRACT
The special reflection phenomenon of seismic waves on the large-scale underground water-bearing body has been discovered from a seismic method advanced prediction. According to the classical theory of seismic wave reflection and transmission, this phenomenon has been explained. In order to verify the correctness and applicability of the conclusions, two field tests have been carried out in Qingdao Jiao Zhou sub sea tunnel. TSP method was used to detect the seafloor in the field tests of sub sea tunnel, and the results verify the special laws of seismic wave reflection. According to the field tests conclusions and engineering examples, seismic wave reflection laws have been summarized. In engineering practice, especially for advanced geology prediction the laws have important application value.

ARMA 10-204

Rock Fragmentation Module in 3-D Rock-fall Analysis

Y., Wang[1,2], F., Tonon[2], G. B., Crosta[3], F., Agliardi[3], Z.M. Zavodni[4]
[1]Shannon & Wilson Inc., Jacksonville, FL, USA

[2]The University of Texas at Austin, Austin, TX, USA
[3]Universita' degli Studi di Milano Bicocca, Dip Scienze Geologiche e Geotecnologie, Milano, Italy
[4]Rio Tinto, Salt Lake City, UT, USA

ABSTRACT
A fragmentation model to predict rock fragmentation upon impact in rockfall modeling was developed utilizing the impact simulation results obtained using a discrete element code developed by the first author. The code was validated in static and dynamic regimes. Because it takes a relatively long time to run an impact simulation directly using the developed discrete element code, a large set of impact simulations covering different impact scenarios has been carried out to populate a database. This database was then used to construct a fragmentation module by either neural network model or multidimensional linear interpolation. The details of the fragmentation module are presented in the paper. The developed fragmentation module using the interpolation method has been successfully integrated into the existing 3D rockfall simulation code HY-STONE to perform rockfall analyses that account for impact fragmentation.

ARMA 10-205

Measurement of Fracture Aperture in Granite Core Using Microfocus X-ray CT

Nakashima, S
Yamaguchi University, Ube, Japan

Hasegawa, D. and Kishida, K.
Kyoto University, Kyoto, Japan

Yasuhara, H.
Ehime University, Matsuyama, Japan

ABSTRACT
Microfocus X-ray CT imaging was conducted on a granite core, 50 mm in diameter and 100 mm in length, containing a single fracture in the longitudinal direction. The three-dimensional geometry and the aperture distribution of the fracture were evaluated by analyzing the CT data. A very notable artifact called beam hardening was found in the obtained CT images because of the high X-ray absorption coefficient of the material compared with the source intensity of the X-rays. To reduce this phenomenon, two methods were applied when handling the CT data. One was to consider the slice direction when detecting the fracture route, and the other was to correct the CT data using a simulated image of the beam hardening of granite. Moreover, we developed a procedure to determine the fracture route automatically from the CT image. As a result, the spatially averaged aperture thickness and the contact ratio of the fracture asperities under unconfined conditions were estimated to be 0.39 mm and 2.0%, respectively.

ARMA 10-248

A DEM Study on Perforation Induced Damaged Zones and Penetration Length in Sandstone Reservoirs

Nabipour, A., Sarmadivaleh, M., Asadi, M.S., Sabogal, J. and Rasouli, V.
Curtin University of Technology, Perth, WA, Australia

ABSTRACT
During a perforation job an opening is made in the formation to act as a conduit for hydrocarbon to be produced from the reservoir and flow into the wellbore. This process induces some degree of damage to the surrounding rocks which increases the wellbore skin and consequently decreases production. In this study the perforation job is simulated numerically using PFC2D which is a 2D DEM code to evaluate the length of perforation tunnel (LPT) and the extent of damaged zone (EDZ). Formation is modeled as an assembly of bonded particles with assigned micro-mechanical properties. Furthermore; formation macro-mechanical properties were obtained by performing a series of simulated biaxial tests. High velocity perforation agent was shot against the formation which generated the perforation tunnel as a result of particles displacement and bonds breakage. The results showed that LPT and EDZ are influenced by perforation direction, particle size distribution, formation porosity, and magnitude of in-situ stress. Perforation into formations with smaller particle size ratios and lower porosities results in less LPT and EDZ. The LPT reaches it maximum limit in the direction of maximum horizontal stress. In addition, the higher the value of isotropic horizontal stress, the lesser would be the LPT and the EDZ.

ARMA 10-254

Comparative Study Using Rock Energy and Drilling Strength Models

Rashidi, B., Hareland, G., Fazaelizadeh, M. and Svigir, M.
University of Calgary, Calgary, Alberta, Canada

ABSTRACT
Drilling simulation technology has been used extensively to optimize drilling operations to obtain the lowest costs and risks. One of the challenges during drilling operation is to use the energy at the drill bit more efficiently. Mechanical specific energy (MSE) is defined as the amount of energy required to destroy a given volume of rock. It can be used to predict and analyze the power required for a specific bit type in a given rock for a specific rate of penetration. Rate of penetration models, on the other hand, can be applied in all drilling phases, including well planning in areas where offset well data is available. In this paper, a study was conducted to demonstrate the effects of changing the drilling parameters, bit wear and bit designs on ROP for both approaches. Optimum bit types and designs with corresponding drilling parameters can be "globally" recommended for entire bit runs using the ROP model. The MSE model can be used to adjust the operating parameters to reach a maximum ROP value "locally", or in real-time, with no effects of bit design or bit wear integrated. The flexibility of using an ROP model as opposed to the MSE equation transformed into an ROP equation is also investigated.

ARMA 10-263

Quantify Uncertainty of Rock Failure Parameters from Laboratory Triaxial Testings using Conventional and Multistage Approaches

Dung T. Tran, Aristotelis Pagoulatos, Carl H. Sondergeld and Jean-Claude Roegiers
Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Norman, Oklahoma, USA

Nam Nguyen Canh
Department of Mathematics, Technical University of Denmark, Lyngby, Denmark

ABSTRACT
Rock mechanical properties and Mohr-Coulomb failure envelope are mainly obtained from laboratory triaxial testings. Conventional triaxial testing approach is simple but requires multiple samples; thus, uncertainty arises from sample heterogeneity. Multistage testing of a single sample resolves the heterogeneity issue, requires less time and is less expensive. However, uncertainty arises from how one relates non-failure Mohr circles to failure ones, and how one specifies a criterion for the termination point of each loading stage. In this study, based on conventional and multistage triaxial testings of Berea sandstones, the inflection point of the volumetric strain curve is proposed as the termination point for each loading stage. The results from both approaches are shown to be comparable but uncertainty is reduced with multistage testings. Finally, a new analytical solution to find the best-fit failure envelope based on least-absolute errors is presented.

ARMA 10-273

Microseismic Validation of Jointed Rock Models in Cave Mining

Reyes-Montes, J.M. and Pettitt, W.S.
Applied Seismology Consultants, Shrewsbury, United Kingdom

Pierce, M.E.
Itasca Consulting Group, Minneapolis, Minnesota, USA

Young, R.P.
University of Toronto, Ontario, Canada

ABSTRACT
Inducing fractures in rock masses is current practice for the exploitation of deep ore bodies and the optimization of production in petroleum reservoirs and enhanced geothermal systems. The combination of microseismic field observations with numerical tests provides a tool to enhance the knowledge of the mechanics of the induced fracturing. The enhanced analysis of microseismicity recorded during the block-caving of a deep underground ore body is used to interpret the nature and geometry of the induced fracture network and serves as a primary validation tool of the Synthetic Rock Mass (SRM) numerical models built to reproduce the nature of the rock and the stress conditions imposed during production. The rock is reproduced by an assembly of bonded particles with an embedded Discrete Fracture Network (DFN) to represent open joints. SRM samples subjected to the same stress disturbance expected in the field produce a series of bond breaks and joint slips that are clustered into synthetic microseismic events. The models provide an interpretation of the causal effects of the microseismicity by analyzing the micromechanics within the numerical model. Microseismicity provides feed back into the development of the SRM models, and so validate their results, in order to develop robust predictive models.

ARMA 10-298

Investigation into the Stability of Rocks Surrounding Gateway Affected by Coal Pillar Width in Deep Mining

Ke Yang
Key Laboratory of Coal Mine Safety and Efficiently Caving of Ministry of Education, Anhui University of Science and Technology, Huainan, Anhui Province, China

ABSTRACT
A key issue in deep underground mining is to understand and master the evolving patterns of mining-induced stress, and to control and utilize the action of rock pressure, especially for designing safe and economic coal pillar widths. Different coal pillar widths result in differences in deformation, stress and movement of rocks surrounding the gateway and strongly influence the stability and maintenance of the gateway. Based on numerical simulation, the characteristics of deformation, stress and movement of rocks surrounding gateway and the stability of gateway was synthetically investigated. The results show that the stress distribution and deformation characteristics of surrounding rock vary with different pillar widths during caving. Stress distribution in the coal pillars and changes with different pillar widths. The allowable deformation and stability of the opening are based on the stress distribution and developing a critical stress-width relationship.

ARMA 10-300

Test Study on the Changing of the Porosity for Water-Saturated Granular Shale During its Creep

Ma Zhan-Guo
State Key Laboratory for Geomechanics and Deep Underground Engineer (China University of Mining & Technology), Xuzhou 221008, China

Peng Wang, Guo-Zhen Zhao, Kai Sun and Jin-Quan Fan
School of Mechanics & Civil Engineering, Xuzhou 221008, China

ABSTRACT
Deformation properties and seepage characteristics of broken rock under the water saturation state is always the great subject during the deep mining. Broken rock shows significantly creep properties. Creep behavior caused the continuous variation of pore as well as the seepage characteristics. The change law of pore of saturated broken shale during creep process is studied through a experimental device for multiphase coupling and creep of broken rocks. The effect of axial stress and grain size on the porosity is analyzed. The results show that in the broken shale's creep process the porosity is negative exponent linear dependence relation with time n = n0 + a e- bt, there n is the porosity of granular shale, t is time, n0 is the porosity at the stabilization phase, a , b are the Regression coefficient, and n0 , a ,b are decided by the particle size and the load, and the whole process has obvious stage: when the load is same, the smaller the crushing shale's particle, the smaller the change of its porosity, and then the porosity is larger in the end when the process is stable. As the load increasing, the difference of the porosity caused by the different crushing shale's particle dimension becomes smaller and smaller; in the same shale's particle dimension,one with larger load has a quicker change of porosity than the small ones. In the initial period stage of creep, the particles are easy to slide because of bad balance between the granular shale, and the porosity of every particle sizes rock sample reduces quickly; When after a period of time, the amount of particles broken increase, more and more fine particle have filled the pore between broken rocks, the granular shale become more denser, the porosity reduces slowly, then tends some stable value finally.

ARMA 10-301

A Case Study on Translational Failure of Sedimentary Cut-Slopes in Korea

Seung Hyun, Kim, Ho Bon, Koo and Ji Yong, Choi
KICT, Koyang, Gyeonggi Province, S.Korea

Young Eun, Park and Nam Gyoung, Hong
MLTM, Gwacheon, Gyeonggi Province, S.Korea

ABSTRACT
On the Korean Peninsula, the Southeast region mainly consists of cretaceous sedimentary rocks. The bedding dip increases from inland toward the sea. Numerous cut-slopes have been created for new road construction and two slopes located in inland had a particular failure and rock slide (bedding's dip is less than 10 degrees) as in translational failure. One slope in the Jinju area (following "Jinju Slope") had several failures in 2007 and mitigation for stabilization was resloping at a dip is 30 degrees. In May 2009, tension cracks with widths of 10~20 cm developed in the upper part of the slope and sliding along the bedding occurred due to heavy, regional rainfall. The other slope in the Gwangyang area (reffered to as the "Gwangyang Slope") exhibited an unprecedented depression along vertical discontinuities in center of the slope. Gwangyan Slope consist of alternating of sandstone and shale. In particular, a reddish, shale layer is a fractured zone and the upper part of this reddish shale layer shows bulging and tensile cracks. We estimated kinetic displacements and safety factor for the two slopes using MIDAS/GTS based in finite element analyses.

ARMA 10-302

The Influence of a Weak Structure Instability of a Deep Rock Roadway Subjected to a Stress Wave

Ai-Hong Lu, Peng Wang and Xian-Biao Mao
State Key Laboratory for Geomechanics and Deep Underground Engineering and School of Mechanics and Engnieering, China University of Mining & Technology, Xuzhou, Jiangsu, China

ABSTRACT
Energy accumulation and its distribution are two main factors to be used to judge rock burst occurrence. An energy density criterion to distinguish the danger of rock bursting is put forward based in this paper. In order to absorb more energy, a weak structure is set in the surrounding rock. The process of energy accumulation and the effect of the weak structure on the energy accumulation were simulated and analyzed by employing ANSYS/LS-DYNA. The characteristics and the position of the energy accumulation were obtained. The results show that the stress wave is an important factor making energy accumulate in the surrounding rock resulting in rock bursting; moreover, the weak structure decreases the value of the maximal energy density (Ud)max and increases the distance between its position and the surrounding roadway, namely the value of energy density factor, k. The properties of the weak structure control the value of the energy density factor. The results are significant for the study of inducing mechanisms and the prevention of rock bursts.

ARMA 10-326

The Effect of Boundary Conditions on the Creep Behavior of Salt Rock using Numerical Modeling

Jafari, M. , Moosavi, M.
School of Mining Engineering, The University of Tehran, Tehran Iran

Mahmoodyan, E.
School of Mechanical Engineering, The University of Tehran, Tehran Iran

ABSTRACT
Methods such as impression creep test have been used to measure creep parameters in metals and alloys, glasses, ceramics and polymers. Recently, this kind of creep test has also been carried out on soft rocks such as mudstone and salt and good results have been achieved. In this paper, using numerical modeling, this test is compared with compression creep tests. Additionally, the effects of model dimensions on the activation energy and power exponent values are discussed. The results show an insignificant effect on the boundaries on the obtained results.

ARMA 10-341

Slope Stability at Chador Malu and Optimization of the Monitoring Systems

Aloodari, S., Ahangari, K. & Naeimi, Y.
Mining Engineering Department, Science and Research Branch, Islamic Azad University, Tehran, Iran

Noorani, R.
Metra Consulting Engineers Co, Tehran, Iran

ABSTRACT
Choosing the accurate slope of open pit, both from the stability and financial point of view, is by far the most vital part of mines design procedure. On the other hand, monitoring systems could be utilized so as to understand the behavior of rock mass. In the current study, slope stability of Chador Malu open pit was assessed. In this research, various models for both current pit with 50m depth and also final pit have been investigated and the appropriate monitoring systems were recommended.

ARMA 10-352

A General Investigation on Slope Stability at Khersan Iii Hydropower Plant using Numerical Modeling

Jafari, M.A.
School of Mining Engineering, College of Engineering, Tehran, Iran

Ashtiani, M. and Palassi, M.
School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran

Fattahpour, V.
School of Mining Engineering, College of Engineering, University of Tehran, Tehran, Iran

ABSTRACT
The study of the slope stability of surface structures such as a surface hydropower plant is an important task which should be considered by rock mechanics experts. This paper deals with the large-scale slope stability of hydropower plant of Khersan III dam in Iran. Existence of some factors such as sharp scarp on the top of this slope emphasizes the importance of this study. In this paper, firstly, the stability of this slope is analyzed using numerical modeling and secondly the rock fall analysis is presented.

ARMA 10-353

Prediction of Standard Penetration Tests via Microtremor Array Using Artificial Neural Networks

Angorani, S.
School of Mining Engineering, University of Tehran, Tehran, Iran

Memarian, H.
School of Mining Engineering, University of Tehran, Tehran, Iran

Shariat Panahi, M.
School of Mechanical Engineering, University of Tehran, Tehran, Iran

ABSTRACT
In recent years, artificial neural networks (ANNs) have been applied to many geotechnical engineering problems with some degree of success. In this paper, an ANN model is developed for predicting standard penetration tests (SPT) by microtremor array results. SPT gives an indication of the soil stiffness, which can be empirically related to many engineering properties. Microtremor is a low amplitude ambient vibration of the ground, caused by man-made or atmospheric disturbances and gives useful information on dynamic properties of the studied site, such as ground predominant period and amplitude. Using microtremor array shear wave velocity profile was obtained. An ANN was trained with Vs and SPT measurements in 7 boreholes with 100m depth as input and output, respectively. The present study shows that using an optimized ANN model, the SPT can successfully be estimated from a microtremor array, which eliminates the necessity of having excessive boreholes.

ARMA 10-371

Crustal Deformation History of the Tsushima Island and its Vicinity, Japan, During the Cenozoiz Teritiary

Honggyun Kim, Hoobon Koo and Ferdinand Estudillo Bautista
Korea Institute of Construction Technology (KICT), Goyang, Kyonggi-Do, Korea

Cheol Woo Song and Moon Son
Pusan National University, Busan, Korea

ABSTRACT
In Tsushima Island, it is interpreted that the NS or NNE-SSW trending tensional stress field induced the dextral strike slip movement of the Tsushima-Goto faults during Late Oligocene and that initial rifting of the basin occurred. And the tensional and southwesternmost part of Japanese Arc caused clockwise horizontal rotation of the southern part of Honshu, which generated Tsushima Island. At that time, the folding of San'in folded zone was commenced. The folds in the Tsushima Island was almost completely formed at about 15 Ma and then an extensive intrusion of felsic magma occurred in the southern part of the island, which led the island to be tilted about 20 degrees into northeast. Simultaneously, the Tsushima-Goto faults were reactivated as major sinistral strike-slip faults owing to the accumulated NNW-trending compressional stress. The adjacent blocks to the faults were rotated about 28 degrees counter clockwise caused by the sinistral strike-slip movement. Resultantly, the western part of the San'in folded zone was dragged counter clockwise.

ARMA 10-391

Open Pit and Underground Mine Interaction with Phase 2

Cordova, E. A. and Nelson, M. G.
University of Utah, Salt Lake City, Utah, USA

ABSTRACT
There are a number of mines analyzing the possibility of doing the transition from open pit to underground, underground to open pit, or extending the production and having both mining methods working at the same time. In each case at some point in time during the transition or when both mining methods are in place, there will be an interaction between surface and underground workings. This may prove to be beneficial to the underground operation, by helping the rock to cave and relieving the concentrated stresses surrounding the rock mass in the underground. On the other hand, it may create unwanted effects in the pit, producing instability in the areas closer to the underground operation, deteriorating the haulage

roads, and generating slope failures and unsafe working conditions. Understanding the general effects of the interaction between both mining methods at a two-dimensional level is an important start-up point to study mine planning options, time schedules, and proposed designs before going into a more detailed and time consuming three-dimensional modeling. The software Phase2 was used to simulate the interaction of a subsidence cave with broken material generated from an underground project lying underneath and an open pit project that is being developed in surface. Different stages were used to create a time line for the planned advance of the underground mine, and the open pit evolution.

ARMA 10-429

Influence of Groove Geometry and Cutter Inclination in Rock Cutting

Richard, T.
CSIRO, Perth, Australia

Coudyzer, C.
Faculte Polytechnique, Mons, Belgium

Desmette, S.
Diamant Drilling Services, Gosselies, Belgium

ABSTRACT

The paper deals with the influence of the cutting geometry on both the magnitude and orientation of the cutting force acting on a sharp cutter tracing a groove on the surface of a rock sample. Tests were carried out with various cutter geometry (circular, triangular and rectangular) and cutting configuration (back and side rake angles, overlapping grooves) on various soft sedimentary rocks at shallow depth of cut (typically less than 1 mm). At shallow depth of cut, it is commonly assumed that the magnitude of the force mobilized on the cutting face is proportional to the cross-sectional area of the cut (the coefficient of proportionality is referred to as the intrinsic specific energy Σ) and that the inclination ψ of the cutting force is controlled by a uniform frictional process between the failed material and the cutting face. However, the results reported in this paper clearly show that the geometry of the groove being traced can strongly affect the magnitude of the intrinsic specific energy, indicating that the cutting process should be modeled as a 3D process. They also reveal that the angle ψ is not controlled by a uniform flow on the cutting face. An interpretation introduces the presence of a build up edge of crushed material formed at the bottom of the cutting face. This edge controls the distribution of the flow in 3D in front of the cutting face in such a way that the inclination between the force and the cutter velocity is almost independent of the cutter inclination (both the back and side rake angles).

ARMA 10-431

Digital Image Correlation and the Fracture Process in Rock

Qing Lin & Joseph F. Labuz
Civil Engineering, University of Minnesota, Minneapolis, MN USA

Sara Cattaneo
Structural Engineering, Politecnico di Milano, Milano, Italy

ABSTRACT

The propagation of fracture in rock is associated with a process zone in the form of a localized region of damage. Digital image correlation was employed to observe the process zone based on the measurements of the surface displacement field. A Berea sandstone beam with a center notch was tested in three-point bending and a charge-coupled device camera was used to acquire digital images. The images were concentrated on the area surrounding the notch and were processed using a cross-correlation algorithm based on the Fast Fourier Transform approach. The process zone was identified from the detailed measurements of the displacements related to the region surrounding the tip of the notch. In particular, the initiation of fracture was characterized by a region of localized damage. Furthermore, a traction-free part of the fracture was found from the measured displacement profile after sufficient propagation.

ARMA 10-470

Geomechanical Data Acquisition and Modeling Applied to an Offshore Sandstone Petroleum Reservoir

Sousa Jr, L. C.
Petrobras E&P-ENGP/RR/Reservoir Engineering, Rio de Janeiro, RJ, Brazil

Santos, E. S. R and Ferreira, F. H.
Petrobras Research Center – CENPES, Rio de Janeiro, RJ, Brazil

ABSTRACT:
This paper documents a geomechanical simulation of an oil field in order to devise safe injection pressure boundaries to avoid inducing hydromechanical reservoir issues. Cap rock integrity and fault reactivation are the main concerns. The reservoir rock is an unconsolidated sandstone over an area of 80km2 at an average depth of 2700 to 2900m under water depths ranging from 1000 to 1200m. The reservoir production began with nine horizontal producer wells and the supplementary oil recovery project is being implemented with eight water injection wells. A review on methods and techniques to acquire rock deformability, strength and insitu state of stress data from well log correlations and special well operations is presented here while devising information for this specific oil field. Like any other physical measures, these information and consequent judgments present a high level of uncertainties and the amount of data gathered also plays a role in identifying the global data trends, attempting to achieve more realistic results. The pore pressure changes along time were calculated by a reservoir fluid flow simulator and an elastoplastic nonassociative finite element code was used to perform the structural analysis. The simulations showed that the analyzed faults remain stable in the choosen production project. The over-pressurized area induced by water injection increased the minimum horizontal total stress, reducing the stress contrast between the reservoir and cap rock. Fluid injection above fracture propagation pressures should be avoided.

ARMA 10-474

Stress Effect on Compressibility of Weakly Anisotropic Micro-Fractured Rocks a Study Case on Colombian Foothills Tight Sandstones

Carvajal, J. M. and Saavedra, N. F.
Ecopetrol S.A., Bucaramanga, Santander, Colombia

Calderon, Z. H.
UIS, Bucaramanga, Santander, Colombia

ABSTRACT
The present study is focused on understanding the rock compressibility behavior under different stress paths, various stress ranges and a series of micro-fracturing levels of the weakly anisotropic micro-fractured sandstones from Colombian Foothills formations Mirador and Barco. Laboratory results show that compressibility behavior depend on both stress path and stress state. The rock compressibility on tested samples decreases as stress pathway. Results also show that as mean stress applied on rock increases the compressibility decreases and that for low mean stress values the decrease on compressibility is faster than for higher stress values. Finally, micro-fracturing density increases both the stress sensitivity and the initial value of rock compressibility but this increase is not as drastic as the one due to stress pathways. The experimental observations found in this study were used to build a numerical model to predict compressibility changes on Mirador a Barco Formations which can be used during reservoir evaluation.

ARMA 10 – 476

Water Imbibition in Oilfield Rocks: Experimental Data and Comparison to Theoretical Models

Martin Webiao Suarez – Olympus High School
Roberto Suarez-Rivera – TerraTek, a Schlumberger company

ABSTRACT
In last year's ARMA conference, we presented experimental results of spontaneous imbibition of water based fluids to nine oilfield rocks (8 sandstones and a limestone), and evaluated water suction capacity as a function of time. We showed that the measured imbibed water was proportional to the rock porosity; and that the rate of imbibition was a function of wettability (or the rock suction potential). We also demonstrated experimentally that the mass of water imbibed and the fraction of the imbibed pore volume are proportional to the square root of time. These results are in line with the one-dimensional theory of capillary suction. Different rocks have different slopes and these were measured experimentally and provided in the paper. We also noted important departures from the linear theory during the early and late times, the square root of time relationship was no longer linear. We postulated that this was possibly due to boundary effects associated to the enhanced connectivity at the surfaces, and the small size of the laboratory samples. The paper elaborates on these non-linear boundary effects by comparing the measured data and a theoretical model published by Robert Zimmermann. We show that the theoretical model is in good agreement with the measurements and help understanding the physics of these effects. Although end effects associated to abnormal connectivity at the free surfaces may at first glance be considered of limited importance, we believe that this effect is significant to the problem of water imbibition during hydraulic fracturing of low permeability rocks (gas shales and tight gas). Under these conditions, the volume of imbibed water with time (during pumping) could be significantly larger than the amount predicted using the one dimensional theory. This result in important implications to the created surface area created (potentially much smaller than anticipated assuming low imbibition) and to the reduction is gas production (because of associated gas-water relative permeability effects).

ARMA 10-481

Top Coal Deformation Characteristics of High Section Fully-Mechanized Top-Coal Caving for Extra-Steep-Thick Seam

Miao, S.J.
Civil & Environmental Engineering School, University of Science and Technology Beijing, Beijing, China

Lai, X.P., Cui, F., and Cao, J.T.
School of Energy Engineering, Xi'an University of Science and Technology, Xi'an, Shanxi, China

ABSTRACT
Compared with gentle dip long-wall fully-mechanized top-coal caving, workface length of top-coal caving for extra-steep-thick seam is short, so increasing section height of sub-level is one of the effective methods that can increase production. Meanwhile there are some challenges, such as low caving ratio, roof falling induced by local and large area collapse of top coal in workface, and injury induced by gas accumulation. After crack weakening of high section top coal for extra-steep seam (over 60°), broken top coal (granular medium) has obvious nonlinear movement characteristics. Geological occurrence environment and mining condition of excavation disturbed zone was thoroughly analyzed, based on simulation experiment results of large-scale 3D and coupling of top coal-water-gas, top coal after weakening was regarded as non-continuous medium, Particle Flow Code program was used to compare and analyze motion process and law of high section (30 m) top coal before and after weakening for extra-steep seam of Weihuliang coal mine. Mining experiment and monitor results show that water pre-infusion and pre-splitting blasting can improve top coal caving ability, symmetrical caving, relieve space for large area dynamic collapse of top coal, prolong motion time of noxious gases and escape it from mined out area to realize safe mining.

ARMA 10-487

Development of a Damage-Based Constitutive Model for Brittle Rocks

Mortazavi, A. and Molladavoodi, H.
Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran

ABSTRACT
The dominant causes of irreversible rock deformations are damage process and plastic flow. Most of the existing elastic-plastic models employed in the analysis and design of rock structures only consider the plastic flow and ignore the full damage process. Therefore, developments of realistic damage models are essential in the design process of rock structures. In this paper, the basic concepts of continuum damage mechanics are outlined and a clear definition of the damage re-

sistance function and its hardening and softening laws are established. Since quasi brittle materials such as rock degrade under shear microcracking (mode Π), separate positive and negative damage yield functions are introduced. The proposed damage yield functions are formulated in the framework of a damage model which was coded in C++ environment and implemented into the commercial code UDEC. Accordingly, the developed algorithm was applied to the simulation of brittle rocks behavior. The uniaxial compressive and tensile testing of a brittle rock was simulated numerically and numerical findings were compared against experimental data. The analysis results show a very good match between numerical and experimental data especially in the post-elastic region.

ARMA 10-495

Advanced Strain – Hardening Approach Constitutive Model for Rock Salt Describing Transient, Stationary, and Accelerated Creep and Dilatancy

Ralf-Michael Günther, Klaus Salzer and Till Popp
Institut für Gebirgsmechanik GmbH, 02479 Leipzig, Saxony, Germany

ABSTRACT
In the scope of a unified approach to describe the creep behavior the constitutive model as presented here describes comprehensively the mechanical behavior of rock salt in a good approximation. In this model, hardening is used as an inner variable of state. This model has been verified by the results which were obtained when recalculating different laboratory tests. Evidently, hardening is governed by the processes of deformation and recovery on the one hand and by those of damage on the other one, i.e. the formulation of the constitutive law is based just on those processes of crystal physics which are the origin of the mechanical behavior of salt rock. These considerations have allowed demonstrating that the hardening-reducing effect of damage can be put on the same level as the dilatancy, the latter being a function both of deformation work performed above the dilatancy boundary (dilatancy work) and minimum stress which has to be determined from triaxial tests. The paper contains a complete set of equations, which are used in model calculations.

ARMA 10-507

A Sensitive Analysis on Mohr-Coulomb and Hoek-Brown Parameters Effective in Ground Response Curve

Kargar, A.R. & Rahmanejad, R.
Department of Mining Engineering, Shahid Bahonar University of Kerman, Iran

ABSTRACT
Selecting appropriate failure criteria is very important in the analysis since it affects on plastic zone and on the resulted displacement and stress field around the opening. Some closed-form solutions have suggested for the ground reaction curve, although they are driven based on elastic-perfectly plastic or elastic-brittle-plastic models of rock mass behaviour. Brown et al (1983) proposed a stepwise procedure based on Hoek-Brown criterion to solve stress and displacement around the circular opening for elastic-strain softening model of rock mass behaviour. A similar stepwise procedure was extracted in this study for Mohr-Coulomb criterion. Finally a sensitive analysis was implemented for Mohr-Coulomb and Hoek-Brown criteria in respect to their parameters

ARMA 10-510

Numerical Modeling of Mechanical Behavior of a Jointed Rock Mass

M. Asadizadeh & R. Rahmannejad
Dept. of Mining Engineering, Shahid Bahonar University of Kerman, Iran

ABSTRACT
An assessment of mechanical behavior of jointed rock masses is an essential requirement in the site selection, design and successful execution of Civil and Mining Engineering projects. A quick estimate of these properties for preliminary evaluation of alternate sites will reduce considerable expenditures for field tests. A large number of tests on a jointed rock mass

with various joint configurations had been done by Mahendra Singh and others. In this present study, an attempt has been made to compare the results between numerical simulation of experimental modelling on strength and deformability of jointed block masses. For this purpose, numerical simulation of experimental tests for rock mass modulus and strength has been done by 3 Dimensional Distinct Element Code (3DEC). Results showed numerical simulation and experimental testes have good agreement.

ARMA 10-512

Large Scale Experiment Study on Reinforcement Effect of Rock Bolt to Intermittent Jointed Rock Mass

Yang, W.M. & Li, S.C.
Geotechnical and Structural Engineering Research Center of Shandong University, Jinan, Shandong, China P.R.

Li, X.J.
Shandong Jianzhu University, School of Civil Engineering, Jinan, Shandong, China P.R.

ABSTRACT
Intermittent jointed rock mass is common in rock engineering. The original joints propagate, coalesce and lead to failure of rock mass. Rock bolt could prevent or postpone crack opening and propagation. In present study, a series of large scale experiments were performed, aiming to study the reinforcement effect of rock bolt to intermittent jointed rock mass. Mortar was selected to be rock-like material. Multi-crack samples were prepared according to different crack arrangement by changing crack length, spacing, connected ratio, and dip angle. Uniaxial tests were carried out for both unbolted case and bolted case corresponding to every crack arrangement. Comparative analysis was performed on the basis of test results.

ARMA 10-515

Numerical Simulation of Large Diameter Bored Pile of High Pressure Jet Grouting

Jin Li & Peng Hu
Civil Engineering Department of Shandong Jiaotong University, China

ABSTRACT
By the MARC program, the spatial axisymmetric finite element model of single pile was established; and by the Visual-Fortran program, the function of large common finite element program MARC had been developed forming two Subprograms: SUBROUTINE UINSTR for soil initial stress analysis and SUBROUTINE UFRIC for dynamic contact analysis. Based on the model, influence of injecting cement's modulus and thickness on the bearing performance of the large diameter bored pile is analyzed and the following results have been obtained: (1) the injecting cement's modulus around pile has little influence on the bearing performance of pile; (2) injecting cement's rational thinness around pile is 18-25cm; (3)by injecting cement around and under the pile, the bearing capacity of pile is improved about 40%,20% and14% when the corresponding length of pile is10m,30m and 50m. The simulation results agree with actual data proving the model is reasonable.

ARMA 10-527

A Neural Network Approach for Predicting the Penetration Depth during Laser Perforation in Limestone

Keshavarzi, R. and Jahanbakhshi, R.
Islamic Azad University, Science & Research Branch, Tehran, Iran.

Nadgaran, H.
School of Sciences, Physics Department, Shiraz University, Shiraz, Iran.

Aliyari, M.
Mechatronics Department of K.N.Toosi University of Technology, Tehran, Iran.

ABSTRACT
Laser perforation is one of the newest techniques suggested as the best candidate for the conventional perforating methods. This is because of its technical and economical priorities over the current shaped charged methods. Generally, some inherent problems exist in shaped charge perforation such as reduction of permeability and formation damage near the perforation tunnel that imposes the costly post-perforation operations. Applying laser perforation increases the permeability remarkably and it doesn't leave any formation damage around the perforation tunnel which shows its prominence. Prediction of penetration depth is so important and useful for evaluating the efficiency of laser perforation. In this paper, an artificial neural network has been developed to predict the penetration depth during laser perforation in limestone. The input parameters which are the effective parameters in laser perforation like laser power, lasing time, saturation and pressure, are related to around 140 laboratory laser perforation tests on limestone core samples and the output is penetration depth in limestone. Finally, the developed neural network has shown a high correlation coefficient with low error and the penetration depth was predicted successfully.

SESSION 22 — **UNDERGROUND MINING**

ARMA 10-317
Ground Support Practices for Low Quality Rock – with Illustrative Examples

Henning, J. G.
Goldcorp Inc., South Porcupine, Ontario, Canada

ABSTRACT
Low quality rock is encountered in many manifestations in underground hard rock mines, ranging from weak and poorly consolidated rock to highly altered or foliated rock. Lateral mine developments driven in low quality rock pose on-going challenges to a mine operator, as ground stability issues, such as caving of under-supported ground, drift closure due to surface deformation or buckling processes, and degradation of exposed rock surfaces are a persistent concern. For many operators, ground support design can be an iterative process, as support practices are refined with time. Using case studies from a variety of underground hard rock mines, this paper reviews techniques for the classification of low range rockmasses and examines the rationale and effectiveness of adopted ground support systems.

ARMA 10-456
Mining Strategies of Multi-Sill Pillars in Burst Prone Ground Conditions at Vale Inco's Coleman Mine

Hosseini, Z. Beruar, O. and Yao, M.
Vale Inco Ltd., Sudbury, Ontario, Canada

Sampson-Forsythe, A.
ITASCA Consulting Canada Inc., Sudbury, Ontario, Canada

ABSTRACT
153 Orebody at Coleman Mine is a narrow vein stringer dipping between 30 to 70 degrees. Current mining extends from the 4250 level to 5100 level. The primary mining method is mechanized cut-and-fill, although drift-and-fill is also used in wider sections of the ore zone. The ore body is divided into six main mining horizons with an average of three mining blocks on each cut. Each horizon is mined upwards towards the next level, creating a diminishing sill pillar. Previous studies have concluded that the suitability of the overhand cut-and-fill technique would require re-evaluation, when the thickness of the crown pillar approaches 60' (20 m), due to high stresses and dynamic pillar failure. When approaching this height, the ground condition in each cut was monitored closely to evaluate the competency of cut-and-fill method. Unfavorable ground conditions started to emerge in the sill pillar of 4550 when mining cut 13 and the sill pillar of 4700 level when mining cut 11, both of which have the slenderest pillars in the orebody with thicknesses of about 30 ft and 50 ft respectively. At about these thicknesses, the intensity and frequency of seismic activity started to increase, mainly in the FW veins and access drifts, as is the characteristics of such narrow vein deposits when using an overhand cut-and-fill method. This paper analyzes the stability of 4550 and 4700 sill pillars through MAP3D numerical modeling and site investigations, and recommends mining strategies to safely and efficiently extract the two sill pillars. The recommendation includes a combination of different mining methods including uppers and underhand cut-and-fill in the high stress zones, and continuing overhand cut-andfill mining in the relaxed zones. The necessary safety measures and ground support requirements are also discussed briefly.

ARMA 10-458

Assessment of Haulage Drift Enhanced Support System - A Case Study

W. Wei, H. S. Mitri
McGill University, Montreal, Quebec, Canada

D. Thibodeau
Vale Inco, Sudbury, Ontario, Canada

ABSTRACT

The paper presents the results of an elastoplastic FLAC modeling study of the rock support performance due to drift excavation and nearby mining activities at the Garson mine of Vale Inco in Sudbury, Canada. The study employs a typical haulage drift section that is 5 m x 5 m and is approximately 1.5 km below surface. The primary support system consists of 2 m long rebars, whereas the enhanced support system includes modified cone bolts (MCB) and a shotcrete liner. The case study is carried out with three analyses. In the first analysis, the primary support system is simulated and the rebar loads are calculated as a result of the drift excavation itself and subsequent extraction of nearby stopes. The second analysis, corresponding to the current practice at the mine, involves the simulation of both primary and enhanced support system together from the beginning of drift development to the end of stope sequencing. In an effort to assess the effect of timing of enhanced support installation, a third analysis is carried out, whereby enhanced support system is installed after the extraction of the first stope. The results are presented in terms of bolt axial loads and stresses in the shotcrete layer. It is shown that the currently adopted support system is sufficient to sustain the effect of mining activities. It is also shown that the delayed installation of enhanced support (after one stope extraction) could reduce bolt yielding of the support system.

ARMA 10-392

Examining the Influence of Stope Strike Length on Unplanned Ore Dilution in Narrow Vein Longitudinal Mining

Hughes, R.
Mining Engineering, McGill University, Montreal, QC, Canada

Mitri, H.S.[1] and Lecomte, Eric[2,1]
[1] Mining Engineering, McGill University, Montreal, QC, Canada
[2] Lapa Division, Agnico Eagle Mines Ltd., Cadillac, QC, Canada

ABSTRACT

Unplanned ore dilution caused by stope wall overbreak can have severe impact on the economics of a mining operation. Parameters like rock mass properties, in situ stress regime, and stope design and construction are known to be contributory factors to ore dilution in open stope mining systems with delayed backfill. This paper presents the results of a case study of the influence of stope strike length on unplanned ore dilution. The study is based on the Lapa Mine of Agnico Eagle Mines Ltd, an underground gold mining operation located in north-western Quebec in the Abitibi region. The mining method is longitudinal retreat with delayed backfill on sublevels of 30 m intervals. Stope dimensions are 12m along the strike and have variable width following the vein. A two-dimensional, finite element model was developed to simulate the longitudinal mining and backfilling process while monitoring ore dilution. The model showed that by decreasing stope strike length the degree of overbreak from both the footwall and the hanging wall can be reduced with the most significant reductions occurring on the problematic footwall.

ARMA 10-113

Rock Excavation and Support for a Crusher Hall at Rana Gruber, Norway

Trinh, Q.N.
SINTEF, Trondheim, Norway

Myrvang, A.
SigmaH, Trondheim, Norway

Sand, N.S.
Rana Gruber AS, Mo i Rana, Norway

ABSTRACT
Rana Gruber is an iron mine in the North of Norway. It is located in a foliated gneiss host rock, and the ore body is about 70 m wide and more than 300 m deep. The ore starts from the surface and continues to go down for more than 300 m deep. Due to this situation, mining cost could be reduced by changing the mining technique from sublevel stoping to sub-level caving. Many underground works have been considered such as field tunnel, transport tunnels, drilling tunnels, shafts and a crusher hall. However, this paper is limited to discuss rock excavation and support of the crusher hall only. The hall is 14 m wide and 23 m high, and need to be designed to accommodate the high horizontal stress and in an "elastic behaviour" rock mass. Numerical models are built for the purposes. This is an updated version of a paper published in Oslo [1].

ARMA 10-517

Finite Deformation Analysis of Displacement Field around a Deep Tunnel

Gao, Y.N.
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology & Department of Civil Engineering, California State Polytechnic University

Gao, F.
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining & Technology

Yeung, M.R.
Department of Civil Engineering, California State Polytechnic University

ABSTRACT
The depth of tunnel excavations has increased in mining practice, as shallower mines have been exhausted. The excavation of a deep tunnel presents many challenges, including high stresses and high tunnel support costs. Therefore, it has become very important to accurately predict the displacement field in the rock surrounding the tunnel, which can then lead to a safer support scheme. In practice, the displacement field can be computed using classical small strain theory. In this paper, we use the finite deformation theory (SR additive decomposition) to compute the displacement field in the surrounding rock and then compare the results obtained with those from small strain theory. Furthermore, we computed using the finite deformation theory the deformation of the surrounding rock, assuming that the rock is viscoplastic. The results show that the difference in the solutions from the two theories is more significant near the tunnel wall, where a fractured and loosening zone can greatly affect the stability of the tunnel. The viscoplastic solution also shows that as time increases, the difference between the finite deformation solution and the small strain solution increases.

ARMA 10-122

Rockburst at Jinping II Tunneling Project

Zhu, H. C., Wu, J. Y., and Zhu, Y. S.
Itasca Consulting China Ltd., Wuhan City, Hubei Province, China

Zhang, C. S., Chen, X. R., and Hou, J.
HydroChina Huadong Engineering Corporation, Hangzhou City, Zhejiang Province, China

Zeng, X. H.
ErTan Hydraulic Engineering Development Co.Ltd., Chengdu City,Xichuang Province, China

ABSTRACT
Rockburst occurrences are mostly resulted from in-situ stress localization in synclines and near faults at Jinping II project. All observed rockbursts have been classified into four types as strain-burst, tip-burst, slip-burst, and fault-induced stain-burst. Stain-burst does not prevail and usually acts as an indication of the increasing risk of severe burst as stress ratio is generally low. Tip-burst is commonly seen and resulted from the in-situ stress localization in the terminating area of NWW-oriented weak fractures at Jinping. Slip-burst, widely reported elsewhere in the world, appeared at Jinping along a stiff facture. Severe stain burst can be triggered when advancing towards a NE-oriented weak fault and thus referred to fault-induced strain burst.

SESSION 23 — **DYNAMICS II: DRILLING/CUTTING MECHANICS**

ARMA 10-439

Cutting Action of Impregnated Diamond Segments: Modelling and Experimental Validation

Franca, L. F. P.
CSIRO – Earth Science and Resource Engineering, Perth, WA, Australia

Lamine, E.
Diarotech S.A. – 95, Chaussée de Charleroi, B-6060 Gilly, Belgium

ABSTRACT
Cutting operations with impregnated diamond segments are characterized by a self-sharpening mechanism, as the gradual wear of the contact surface exposes fresh and sharp diamonds. The performance and life of impregnated diamond segments are thus intimately linked with the wear process of both the diamond and the bonding matrix. Focusing our attention to the construction of interface laws for impregnated diamonds segments, a phenomenological approach is used to describe the cutting action. Firstly, relationships between the horizontal and vertical forces components and kinematical variables (penetration rate v, the angular velocity) are established, considering that the cutting response combines two distinct processes, "pure" cutting and frictional contact that are both rate-independent processes. The paper concludes with a benchmarking of the proposed model with data from laboratory tests conducted with a modified CNC lathe. The results investigated here consider the effect of segment concentration on the cuttability of the segment in tests carried out with a minimum wear rate or contact surface variation. The overall results are in agreement with the model, suggesting that the proposed interface laws can be used to investigate cutting action of impregnated diamond bits.

ARMA 10-206

A New Drilling Rate Model for Tricone Bits and Its Application to Predict Rock Compressive Strength

Hareland, G., Wu, A. and Rashidi, B.
University of Calgary, Calgary, Alberta, Canada

James, J. A.
Husky Energy, Calgary, Alberta, Canada

ABSTRACT
Drilling penetration rate or rate of penetration (ROP) is one of the bit performance indexes. This paper introduces the experimental set-ups for rock failure by inserts of roller cone bits, experiments involved and a method for processing the experimental data. A new drilling ROP model is developed and presented with verification using several groups of lab data. The model is derived directly based on rock craters fractured by a single insert. The work behavior of each insert is not a simple indentation, but includes both crushing and shearing, which represents the actual movement of inserts on a roller cone bit. Finally, the paper focuses on applications of the model in predicting ROP and rock compressive strength with offset well data from Western Canada. The model can reflect the interaction between rock bit and the rock on the bottom hole, and the field verification results are good. The ROP trends from the model match those from the field wells analyzed. In addition, simulations were carried out to predict the unconfined rock strength of formations with the same model using two sets of offset well data. The predicted rock strength matches the strength from log data well, both in trend and values.

ARMA 10-232

Discrete Element Modeling of Rock Cutting Using Crushable Particles

Mendoza, J.A.[2], Gamwo, I.K.[1], Zhang, W.[1], and Lin, J.S.[1,2]
[1] USA Department of Energy, National Energy Technology Laboratory, Pittsburgh, PA, USA
[2] Department of Civil and Environmental Engineering, University of Pittsburgh, Pittsburgh, PA, USA

ABSTRACT
Particle crushing has been observed during rock cutting but its impact is unknown. As part of a comprehensive modeling effort on rock cutting, particle crushing effects were incorporated into discrete elements. The present implementation includes a number of considerations: the particle size dependent crushing strength, computation of the average particle stress, the direction in which a particle should split, and the post crushing configuration. Through the modeling of laboratory crushing tests, inclusion of particle crushing in the modeling gave failure patterns that better matched the laboratory test results. Particle crushing was found to play a significant role when a rock had a relatively high strength or a high stiffness.

ARMA 10-426

Experimental Investigation of Bit Vibration on Rotary Drilling Penetration Rate

Heng Li, Stephen Butt, Katna Munaswamy, Farid Arvani.
Memorial University of Newfoundland, St John's, NL, Canada

ABSTRACT
This investigation evaluated the influence of bit vibration on penetration rate for laboratory rotary core drilling. Laboratory core drill was modified and instrumented to drill under conditions of constant Weight on Bit (WOB) and varying levels of axial vibration amplitudes. Experiments were conducted at 300 RPM and 600 RPM with no vibration and with 60 Hz of vibration at amplitudes of 0.09, 0.29 and 0.44mm. Results show that for WOB less than the founder point, the rate of penetration (ROP) increases proportionally to the amplitude of the vibration. Some tests show that ROP increase is greater near the peak of the ROP-WOB curve. Further laboratory experiments and numerical simulations are planned to investigate this vibration assisted rotary drilling technology.

ARMA 10-524

Thick PDC, Shaped Cutters for Geothermal Drilling: A Fixed Cutter Solution for a Roller Cone Drilling Environment

Durrand, C.J., Skeem, M.R., and Hall, D.R.
Novatek International, Provo, Utah, USA

ABSTRACT
A new, hard, thick, shaped Stinger™ PDC has been developed that aims to provide a link between the rock crushing action of the roller cone and shearing action of the typical fixed cutter to improve both ROP and overall bit and cutter life. The stinger cutter has been shown in laboratory testing to be superior in impact, abrasion and thermal damage resistance when compared to conventional shear cutters. Early stage bit development and testing has shown that the cutters may be suited to hard rock drilling environments where high Weight On Bit (WOB) is typically used. When the cutter is employed correctly in a bit, with appropriate drilling parameters, it can produce significantly larger chips than other types of cutters, reducing the required Mechanical Specific Energy (MSE). The observation of large, oblate chips suggest a novel cutting mechanism that is likely a combination of large contact forces produced by a light setting of relatively blunt Stingers, their radial spacing to kerf the formation, and a static central 'jack' Stinger to regulate the WOB load distribution. With the proper design and operating conditions, the formation fractures under the cutters, the ridges fracture between the cutters, and the central cone of rock fractures under the jack. This arrangement has been shown to improve ROP in field testing. This paper describes the testing of the Stinger cutter and preliminary work on Stinger-populated drill bits aimed to enhance ROP in geothermal and EGS applications.

ARMA 10-434

Modeling Percussive Drilling Performance using Simulated Visco-Elasto- Plastic Rock Medium

Sazidy, M. S., Rideout, D. G., Butt, S. D. and Arvani, F.
Memorial University, St. John's, NL, Canada

ABSTRACT
Optimal force profiles are essential to extracting maximum performance from a percussion drilling system. In this investigation, a visco-elasto-plastic model of rock is simulated using the bond graph modeling formalism to study the effect of different percussive force profiles on rock failure and to generate optimal force profiles. Physical parameters of the model are estimated from rock material properties like compressive strength, density, elastic modulus and Poisson's ratio using Hsieh's equations. The model predicts penetration due to crushing when applied force is greater than a threshold force of the rock medium. This model does not account for penetration due to rotary drilling bit shear or fluid flow. A Specific Energy Index (SEI) and a Performance Index (PI) are employed to evaluate percussive force profiles. SEI reflects the effects of rate of penetration (ROP) and average hammer power whereas PI considers rate of penetration, bit force, and input power. SEI is a limited metric because it recommends low frequencies and low rate of penetration. The Performance Index (PI) seems to strike a better compromise between ROP and power, and has the additional potential benefit of accounting for bit wear. The present model can be studied under both percussive and vibrational loading but here only percussive force profiles are analyzed. The model will be verified experimentally in future investigations.

ARMA 10-289

Pillar Stability Assessment Approach for Mechanized and Drill and Blast Excavations

Bahrani, N. Suorineni, F.T. and Maloney, S.
MIRARCO/Geomechanics Research centre, Laurentian University, Sudbury, Ontario, Canada

ABSTRACT
Stability of pillars is essential in achieving maximum safety and economic values in room-and-pillar and block cave mining projects. Today's economic market is motivating underground mining companies to increase development advance rates and enhance their NPVs. There is a drive to move away from the conventional drill-and-blast as the main excavation method to alternative means such as mechanized excavation. The cyclic nature of drill and blast, and its inherent tendency to damage the surrounding excavation rock mass and increase support demand often result in poor advance rates. There is little experience with mechanized or non-explosive excavation methods in hard rock metalliferous underground mining. Therefore, the perceived benefits of mechanized excavation over drill-and-blast must be demonstrated. The application of numerical modeling in rock pillar stability analysis has recently become popular. In this paper a numerical modeling approach has been developed and used to investigate the impact of excavation method on the stability of hard rock rib pillars. Phase2, the two-dimensional finite element program was selected for the numerical analysis. The 3D advance of two parallel drifts in mechanized and drill and blast excavations is first modeled using the internal pressure reduction approach. The drill and blast excavation is simulated by assigning lower strength and stiffness properties to a zone adjacent to the excavation boundary representing a blast-induced damaged zone, while no such zone is considered to exist in the case of mechanized excavation. The mechanical properties of rock around the mechanized excavation, and the zone outside the perceived blast damage zone are kept the same, and higher than the blast damaged zone. The impact of excavation method on pillar stability is then assessed using the criteria including the distribution of stresses in the pillar, damage initiation and propagation thresholds, strainburst potential as well as depth of yielding.

SESSION 24 — **THERMAL GEOMECHANICS**

ARMA 10-250

Study of Geomechanics in Engineered Geothermal Systems

Johnson, S.M., Ezzedine, S., Hao, Y., and Sun Y.
Lawrence Livermore National Laboratory, Livermore, CA, United States

ABSTRACT: Engineered Geothermal Systems (EGS) have garnered significant attention as a possible source of geographically disperse, carbon-free energy without the environmental impact of many other renewable energy sources. However, a significant barrier to the adoption of EGS is the uncertainty in whether a suitably high heat extraction rate can be economically attained at a particular site. Several mechanisms, which may cause reduced efficiency or effective project failure, have been theorized. Among these, the possibility of local stress changes in the fractured rock mass along with coupling between adjacent fractures, or sets of fractures, may lead to situations where closure of large parts of the fracture network, and the coincident aperture increase of other areas, causes a reduced heat rate. Here we provide details of a coupled fluid-solid mechanics approach (using the Livermore Distinct Element Code, LDEC, and the Non-isothermal Flow and Transport simulation code, NUFT) to determine how different network topologies and flow conditions can enhance or depreciate heat flow rate.

ARMA 10-502

Predicting the Spatial Extent of Injection-Induced Zones of Enhanced Permeability at the Northwest Geysers EGS Demonstration Project

Rutqvist, J., Oldenburg, C.M., and Dobson, P.F.
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Garcia, J., and Walters, M.
Calpine Corporation, Middletown, California, USA

ABSTRACT
We present the results of coupled thermal, hydraulic, and mechanical (THM) modeling of a proposed stimulation injection associated with an Enhanced Geothermal System (EGS) demonstration project at the northwest part of The Geysers geothermal field, California. The project aims at creating an EGS by directly and systematically injecting cool water at relatively low pressure into a known High Temperature (about 280 to 350°C) Zone (HTZ) located under the conventional (240°C) steam reservoir at depths below 3 km. Accurate micro-earthquake monitoring from the start of the injection will be used as a tool for tracking the development of the EGS. We first analyzed historic injection and micro-earthquake data from an injection well (Aidlin 11), located about 3 miles to the west of the new EGS demonstration area. Thereafter, we used the same modeling approach to predict the likely extent of the zone of enhanced permeability for a proposed initial injection in two wells (Prati State 31 and Prati 32) at the new EGS demonstration area. Our modeling indicates that the proposed injection scheme will provide additional steam production in the area by creating a zone of permeability enhancement extending about 0.5 km from each injection well which will connect to the overlying conventional steam reservoir.

ARMA 10-466

Thermally-Induced Tensile Fractures in the Barnett Shale and Their Implications to Gas Shale Fracability

Dung T. Tran, Jean-Claude Roegiers,
Mewbourne School of Petroleum and Geological Engineering, Norman, Oklahoma, USA

Marc Thiercelin
Schlumberger RTC Unconventional Gas, Addison, Texas, USA

ABSTRACT
Recent borehole imaging logs of the Barnett Shale reveal intriguing closely-spaced transverse fractures perpendicular to the wellbore, most often along side with the two common longitudinal drilling-induced tensile fractures. In this study, an analytical wellbore stability model is proposed to inspect the origin of these fractures. The model uses porothermoelastic solutions for a single borehole in a transversely isotropic medium to calculate local stresses and pressure near the wellbore. Tensile and Mohr-Coulomb failure criteria are used to evaluate rock failure. Numerical examples using lab and field data demonstrate that for low porosity, ultra-low permeability rocks, the cooling effect due to ~30 °C temperature difference between the drilling mud and the formation is most likely the cause of the aforementioned transverse tensile failures, even if the shale is assigned a tensile strength > 10 MPa. Whereas, high in-situ stress anisotropy mainly controls the longitudinal tensile failures running parallel to the wellbore.

ARMA 10-313

Rock Mechanical Testing for the Desert Peak Enhanced Geothermal System (EGS) Project, Nevada

Lutz, Susan Juch, Cline, Eric Jason and Martin, J. Wesley
TerraTek, A Schlumberger Company, Salt Lake City, Utah, USA

ABSTRACT
In preparation for well stimulation activities and the development of an enhanced geothermal system (EGS) in the Desert Peak geothermal field, a series of petrologic and rock mechanical tests were conducted on selected core samples to represent the planned stimulation interval within Well 27-15. The interval consists of Tertiary rhyolite tuffs that overlie metamorphic basement rocks consisting of fractured metasedimentary rocks. Hydraulic stimulation of the well is intended to enhance formation permeability through self-propping shear failure along the most optimally oriented and critically stressed of pre-existing fractures. Rock mechanical testing was conducted on core samples to determine mechanical prop-

erties of the various lithologies including: radial versus axial volumetric strain, stress-strain relationships, dynamic versus static Young's moduli, and frictional strengths and failure responses under a variety of confining conditions. The results of the laboratory tests were used to construct Mohr-Coulomb failure envelopes for the proposed reservoir rocks. Comparison of the test results indicate overall moderate rock strengths; with unconfined compression stress estimates of 17,000-27,000 psi (117-186 MPa) for the more siliceous lithologies, and about 12,000- 16,000 psi (82-110 MPa) for argillaceous and devitrified rhyolites. Quasi-static values for Young's modulus and Poisson's ratio ranged from 6538 MPa (in argillaceous rhyolite) to 41,700 MPa (in siliceous metamudstone), and 0.08 to 0.24, respectively. Residual compressive strength measurements were used to evaluate the propensity for frictional failure along natural fractures seen in the stimulation interval within Well 27-15. In the test samples, residual friction angles from constructed Mohr circles determined coefficients of sliding friction (μ) in the range of 0.66 to 0.96. Pre- and post- test measurements on the core plugs indicate up to a 20-fold permeability enhancement in originally tight rhyolite units as a result of shear failure. Assuming that failure occurs on the same structural features in the well as in the core, these laboratory studies directly test the shear dilation concept in these clay-rich rocks, and are being used in combination with borehole stress measurements and fracture logging to predict fluid pressures required for initiation of shear dilation and permeability development within the geothermal reservoir.

ARMA 10-321

Geomechanical Stability during CH4 Production from Hydrates– Depressurization or CO2 Sequestration with CO2-CH4 Exchange

Birkedal, K.A.
Dept. of physics and Technology, University of Bergen, Bergen, Norway

Ersland, G., Husebø, J., Kvamme, B. and Graue, A.
Dept. of physics and Technology, University of Bergen, Bergen, Norway

ABSTRACT
This paper reviews laboratory work, offshore expeditions and numerical models in the open literature on issues related to hydrate and geomechanical stability in submarine and arctic environments. This review is complemented with experimental results of hydrate growth pattern within sandstone pores and subsequent visualization by Magnetic Resonance Imaging (MRI) of methane (CH4) production from CH4 hydrates by depressurization and by carbon dioxide (CO2) replacement. In the depressurization production scheme, the CH4 production was continuously monitored by MRI and all the CH4 originally converted into gas hydrates was recovered. This strategy is based on dissociation of gas hydrate, thus liquid water and methane gas was released under pressure. The second production scheme is based on solid state replacement of CH4. When CH4 hydrate is exposed to CO2 an exchange of gas molecules will occur spontaneously, as CO2 hydrate is the thermodynamically preferred hydrate. The results show the power of MRI as a tool to study hydrate growth pattern and production of CH4 from hydrate-bearing sediments. The role of pore water salinity, gas compositions and gas hydrate stability is discussed. The results show that production based on CO2 sequestration may maintain the structural integrity of the sediments and leave hydrates in the solid state with increased thermodynamical stability.

ARMA 10-156

Stirred-Flow-Through Experiments of Granite under Temperature and pH Conditions Controlled

Yasuhara, H. and Kinoshita, N.
Ehime University, Matsuyama, Ehime, Japan

Nakashima, S.
Yamaguchi University, Yamaguchi, Japan

Kishida, K.
Kyoto University, Kyoto, Japan

ABSTRACT
A series of stirred-flow-through experiments using granite powder has been conduced under temperature and pH conditions controlled so as to evaluate the dissolution kinetics of the Mizunami granite. The well-controlled experiments are carried out at temperatures of 30-70°C and pH 6-13, and a constant flow rate of the permeant fluid is set to be 0.1 mL/min. The system likely reaches a quasi-steady state roughly 100 hrs after the experiments get started. Effluent concentrations are measured by regular sampling for the seven elements of Si, Al, K, Fe, Ca, Na, and Mg that are included mainly in the targeted rock. Relatively high concentrations of Si, K and Ca are observed throughout the experiment. Generically, the higher temperature and pH are prescribed, the faster dissolution rates are evaluated. Subsequently, dissolution rate constants of the granite itself are evaluated using a typical Arrhenius equation and an extended formation taking into account the dependence of pH.

ARMA 10-208

Probabilistic Analysis of Shear Slip of Fractures Induced by Thermomechanical Loading in a Deep Geological Repository for Nuclear Waste

Jaewon Lee, Ki-Bok Min
Department of Energy Resources Engineering and Research Institute of Energy and Resources,
Seoul National University,

Seoul, South Korea
Ove Stephansson

GFZ German Research Center for Geosciences, Potsdam, Germany

ABSTRACT
Various studies have shown that shear slip at existing fractures is an important mechanism for block sliding, increase of fracture permeability, and microseismicity. In the context of a deep geological repository for nuclear waste, the thermal stress generated by nuclear waste is expected to contribute to shear slip and dilation, which will eventually alter the fracture permeability in the region. In this study, the probability of the occurrence of shear slip at a fracture was examined by the Mohr- Coulomb failure criterion. The study was based on the fracture orientation generated by the Latin hypercube sampling (LHS) method, which can improve the efficiency of Monte Carlo simulations by the use of a more systematic approach for selecting the input samples. Statistical data of fracture orientations from the site investigation in Forsmark, Sweden, were used in this study. The historical assessment of thermal stress was based on three-dimensional finite element modeling (FEM) of a geological repository that measures 800 m by 2000 m and on a time scale up to 10,000 years. The results show that the probability of shear slip evolved differently at six selected points due to the difference stresses at each point. However, it was evident that the probability of shear slip was more than twice as large as the initial probability of failure. This increased probability of failure has implications for changes in permeability and microseismicity, which can be an issue during the initial operation of the repository. The study provided a quantitative assessment of the probability of shear slip at a fracture, which is an important parameter for assessing the performance of a geological repository.

SESSION 25 — **WEAK ROCKS AND SHALES**

ARMA 10-258

Large-Scale Laboratory Testing of the Geomechanics of Petroleum Reservoirs

David P. Yale
ExxonMobil Upstream Research, Annandale, NJ, USA

Gina M. Joyce
ExxonMobil Research and Engineering, Annandale, NJ, USA

Arnold P. Kushnick and Steven W. Meier
ExxonMobil Corporate Strategic Research, Annandale, NJ, USA

Sergio A. Leonardi and Todd R. Mayer
ExxonMobil Upstream Research, Houston, TX, USA

Sid C. Shah
ExxonMobil Research and Engineering, Fairfax, VA, USA

Bob Anderson
Precision Custom Components, York, PA, USA

ABSTRACT
A large-scale laboratory for testing a wide range of petroleum recovery and geomechanical processes has been designed and built to provide a test bed for understanding processes before proceeding to field-scale trials of new technology. The system, dubbed LARGE for Large-scale Apparatus for Reservoir and Geomechanical Experimentation, is centered around a 50 ton, 2100 psi rated pressure vessel that allows testing of processes on a "physical model" of the reservoir that is 210 cm in diameter and up to 50 cm thick. Key specifications for the system include an "overburden" spacer to mimic the deformation of the real overburden on the reservoir, pumps and "feed" vessels to simulate injection and production in up to 10 wells, over 450 sensors to measure and image real-time the progress of processes occurring in the vessel, a cooling and heating system to control the temperature of the sandpack between -30 ºC and +90 ºC, and a computer-controlled lab control system to automatically run most processes and collect and process huge amounts of data. They system can be used for a wide range of processes but early work will focus on reservoir processes in shallow, heavy oil reservoirs and overpressured unconsolidated sand reservoirs. This paper also will discuss details of how geomechanics of reservoir processes can be simulated in this system.

ARMA 10-344

Anisotropy, Compaction and Dispersion Characteristics of Reservoir and Seal Shales

Tutuncu, Azra N.
Geomechanics Engineering & Research, Houston, Texas, USA

ABSTRACT
The increased drilling and production operations from unconventional reservoirs has elevated the need for extending our understanding on their complex petrophysical, acoustic, mechanical and failure behavior to incorporate their hydrocarbon production potential. In this paper, the elastic constants and Thomsen anisotropy parameters calculated from the wave velocity data have been compared to those determined from static stress cycling measurements and sonic logs where available. Selected shale anisotropy data from the literature has also been incorporated in the evaluation of the model to emphasize the prediction capability of the micromechanics model for shales. The magnitude of anisotropy has been shown to depend strongly on the organic content and presence of impurities in the matrix along with the fractures while smaller dependence was obtained on porosity. Thomsen parameters (ε, and γ) derived from oriented velocities also indicate frequency dependence that is rarely incorporated in either geomechanical or geophysical models and applications.

ARMA 10-463

Strength, Creep and Frictional Properties of Gas Shale Reservoir Rocks

Sone, H. and Zoback, M. D.
Stanford University, Stanford, CA, USA

ABSTRACT
The deformational properties of gas shale reservoir rocks from the Barnett and Haynesville shale formations were investigated using a triaxial apparatus. The samples tested varied in their mineralogical composition, the degree of diagenesis, the total organic content and the degree of maturity of the organic material. In general, rocks with more cement and less clay show higher elastic moduli, higher intact strength and higher frictional strength. In addition, the amount of time-dependent creep under constant triaxial load correlates strongly with the Young's modulus and clay content in the samples, but does not show any correlation with the Poisson's ratio. Viscoplastic creep in these rocks will impose challenges in effectively stimulating production by slick-water hydraulic fracturing by raising the frac gradient and reducing the amount of induced brittle deformation.

ARMA 10-114

Strength Anisotropy of Mudstones and Shales

Ewy, R. T. and Bovberg, C. A.
Chevron Energy Technology Co., San Ramon / Richmond, CA, USA

Stankovic, R. J.
RSTD Co., Park City, UT, USA

ABSTRACT
Compressive strength anisotropy of six different claystones was measured, using confined triaxial compression tests. Samples were oriented with the bedding perpendicular to the axial stress, and with the bedding at an acute angle to the axial stress in order to cause slip on bedding. Measured strengths were resolved into values of normal stress and shear stress, and these were fit with linear regression to determine values of cohesion and friction angle. Slip on bedding was found to reduce the cohesion by 10% to 70%, and reduce the friction angle by 7% to 17%, with higher reduction generally observed for the lower-porosity rocks. Loading parallel to bedding resulted in the same strength as loading perpendicular to bedding.

ARMA 10-437

Relationships between Unit Weight, Unconfined Compressive Strength, and Deformation Modulus of Vesicular Basalt

Kuhn, B.T. and MacLaughlin, M.M.
Montana Tech of The University of Montana, Butte, Montana, USA

Hudyma, N.
University of North Florida, Jacksonville, Florida, USA

ABSTRACT
The presence of vesicles within basalt has a negative impact on both the unconfined compressive strength (UCS) and deformation modulus (axial stiffness) of basalt specimens. Vesicular basalt specimens (diameters of 44.45 mm) were cored from surface boulders obtained from southern Nevada. Each basalt boulder has its own unique pore sizes, pore spacing, and shape of pores. Sizes of these voids range from less than 1 mm to approximately 30 mm. To date, 26 specimens have been tested in unconfined compression to determine the engineering properties of peak strength and deformation modulus. The variation in these two parameters is assessed as a function of unit weight and total porosity. Results show the specimens fall within two distinct groups, one with relatively high unit weight (low total porosity) and one with relatively low unit weight (high total porosity). The high unit weight (low porosity) specimens had the greatest influence on developed relationships between peak strength or deformation modulus and unit weight or total porosity. Total porosity is a better predictor of peak strength and deformation modulus. Future work is presently underway to investigate potential size effects and characterize various macropore properties to augment the relationships developed through laboratory testing.

ARMA 10-290

Evaluating Properties of Weak Shales in Western Missouri

Maerz, N. H., Magner, K. A.
Missouri University of Science and Technology, Rolla, MO, USA

Likos, W. J., Loehr, J. E., Ding, D.
University of Missouri, Columbia, MO, USA

Miller, A.
Missouri Department of Transportation, Jefferson City, MO, USA

ABSTRACT
Evaluation of the geomechanical properties of shales, especially weak ones is always problematic. The Missouri Department of Transportation (MODOT) recently undertook a major research initiative to achieve significant and recurring cost savings for MODOT by developing improved, technically sound design specifications. Test drilling in shale was conducted;

Boreholes were typically drilled in pairs, side-by-side, with one boring being used for core sampling, and the other being used for in situ penetration testing. Coring methods were modified to provide better quality samples. Testing was conducted on or as near the site immediately after recovery. On site point load testing was introduced and used along with slake durability testing to rank the shale in the Franklin Shale Rating System. Samples of shale too weak for point load testing were tested for plasticity index, which is also part of the Franklin Shale rating system. In the penetration boreholes, alternating split-barrel sampler penetration and Texas cone penetration tests were conducted at 2.5 foot intervals using a standard automatic safety hammer. Between tests, the borehole was cleaned and drilled to the next testing level using a tri-cone roller bit.

SESSION 26 — COAL ROCK MECHANICS

ARMA 10-279

Evolution of Permeability in Coal to Sorbing Gases – A Preliminary Study

Shugang Wang and Derek Elsworth
Department of Energy and Mineral Engineering and G3 Center, Pennsylvania State University, University Park, PA, USA

Jishan Liu
School of Mechanical Engineering, The University of Western Australia, WA, Australia

ABSTRACT
We report laboratory experiments to investigate the permeability evolution of a bituminous coal as a function of applied stresses, pore pressure, and deviatoric stress. Experiments are conducted on 2.5 cm diameter, 2.5-5 cm long cylindrical samples, from the Powellton coal seam, West Virginia. We use a triaxial apparatus at confining stresses ranging from 6 to 10 MPa and axial stresses of 6 -18 MPa. A pressure transient method is used to measure permeability to an inert gas (Helium), a slightly adsorbing gas (Nitrogen), and a significantly adsorbing gas (Carbon dioxide). When pore pressure is kept constant, increasing effective stress causes a reduction in permeability attributed to cleat closure. An increase in deviatoric stress can either reduce or enhance the permeability depending on whether its magnitude is high enough to generate new fractures or low enough to only close the existing cleats. Under invariant total stress, increasing pore pressure increases the permeability to the inert gas (He) but decreases permeabilty to adsobing gases at low pressures and increases permeabilities at high pressures - this behavior is attributed to the competition between coal swelling and changes in effective stress.

ARMA 10-499

Verification of Insitu Pillar Strength for Utah Coal Seams

Hamid Maleki
Maleki Technologies, Inc, Spokane, WA, USA

John C. Lewis
Energy West Mining Company, Huntington, UT, USA

ABSTRACT
As mining continues toward deeper reserves in the remaining western US coal fields, the evaluation of in-situ pillar strength and stability has become important at many operations in Utah, Colorado and Wyoming. Fortunately, site-specific pillar strength methods have been developed for eight US coal seams using in-situ measurements in seven mining districts across the US. These measurements have quantified the higher load carrying capacity of some Utah coal enhanced by high confining stress provided by mostly competent roof and floor rocks and presence of a moderate horizontal stress regime. Based on recent stress measurements in a deep Wasatch Plateau coal mine and stress analyses, the in-situ strength of the Hiawatha/Blind Canyon coal seams are verified. Modeling included the use of two boundary-element codes and one three-dimensional finite difference code to specifically account for the mine stiffness and the confining stress. The study compares boundary element model response for a laminated boundary element code and a more conventional, nonlaminated overburden code while presenting the calculated safety factor plots using the modified Bieniawski method embedded in the laminated code. Detailed FLAC3D modeling of the two seam mains geometries complements the results providing a realistic estimation of pillar stability using the Mohr Coulomb failure criteria.

ARMA 10-370

Swell of Coal Matrix Induced by Gas Sorption and Its Partition to Porevolume and Bulk Strains – A Critical Parameter for Coal Permeability

Meng Lu and Luke D. Connell
CSIRO, Earth Science & Resources Engineering, Bayview Avenue, Clayton, 3168, Australia

ABSTRACT
A novel approach is presented in this text to the representation of the effect of coal sorption strain on cleat porositynand thus the permeability of coal. This involves distinguishing between the sorption strain of the coal, the pores (or cleats) and the bulk coal. The developed model representation is applied to the results from a series of laboratory tests, including the tests for gas adsorption isothermal, the measurement of the swelling deformation of coal with adsorption, the measurement of bulk modulus of coal under different confining stresses and pore pressures, and the multi-component gas species core flush tests, etc. It is shown that the model can quite reasonably well predict the laboratory permeability data. With this model representation proposed the two sorption strain components, i.e., the sorption strain for pores and the bulk coal, are identified through introduction of a parameter for partition between them (with a first order approximation). It is shown that the gas-sorption-induced pore strain is significantly larger than its bulk counterpart; the former is actually approximately 50 times larger than the latter one with the coal sample tested

ARMA 10-500

The Application of And Need for High Density Backfill on US Coal Mines

Spearing, A.J.S
Southern Illinois University Carbondale, Carbondale, Illinois, USA

Brad Gould
Heartland Pumps, Carterville, Illinois, USA

Jeff Champa
BASF, Cleveland, Ohio, USA

Mark Theisinger
Southern Illinois University Carbondale, Carbondale, Illinois, USA

ABSTRACT
The mining and use of coal creates a significant amount of waste materials that need to be safely disposed of. It is likely that in the medium term the Environmental Protection Agency (EPA) in the USA will categorize all such products as toxic which will complicate the disposal of such products and significantly increase the disposal costs. Underground disposal would therefore seem to be the obvious solution especially if the placed material can have low or no permeability so that water table pollution does not present a serious long term issue after placement. Significant advantages could be derived from this backfilling including; the reduction or elimination of surface subsidence, increased extraction, reduced surface waste disposal and the elimination of explosion proof seals in worked out areas. This paper presents the preliminary results of research to date investigating the rheology and advantages of such materials so that distribution systems can be reliably designed.

ARMA 10-271

Water Fusion for Bump Control; Laboratory Feasibility Tests on Utah Coal

M.K. McCarter
University of Utah, Salt Lake City, Utah, USA

ABSTRACT
Water infusion of coal beds has been shown to reduce the potential for dynamic failure of some deep coal seams. It does so by significantly altering the nature of the coal including its strength and brittleness – characteristics also measured by coal bump index tests. Thus the potential for water infusion to reduce the potential for dynamic failure of coal should be evident in laboratory tests where the moisture level is varied. Such tests were conducted on samples of coal and a roof sandstone

taken from the Book Cliffs and Wasatch Plateau coal mining regions of Utah. An innovative testing protocol was devised to prevent oxidation of samples during drying. Moisture was then reintroduced and carefully measured. The decreases in uniaxial unconfirmed compressive strength and static Young's modulus are less than reported for some European coals suggesting that water infusion is unlikely to be an effective means for reducing bumps for the coals tested. However, a roof sandstone showed significant changes in material properties with increased water content, a result potentially significant in predicting behavior of roof strata.

SESSION 27 — ROCK STABILIZATION

ARMA 10-197

Development of a New Yielding Rock Bolt – Yield-Lok Bolt

Wu, Y.K., Oldsen, J.
Jennmar of Canada Inc, Sudbury, ON, Canada

ABSTRACT:
Rock burst is one of the greatest challenges to ground control in the mining industry. There are more and more industry requirements on yielding rock support. Since 2008, Jennmar has been conducting large scale research and development works to develop a technically reliable and cost effective yielding rock bolt. This paper introduces a new yielding rock support - Yield-Lok bolt. The bolt is characterized by the designed yielding ability to produce 150 ~ 250mm of deflection at 8 ~ 10 metric tons (Mt) loads for every 16.4kJ energy input. Its performance characteristics are consistent through multiple and varying amplitude of impacts. In this paper, the design criteria of the bolt and the principle of performance are described; the dynamic testing results are discussed; and the features and application of the bolt are presented.

ARMA 10-217

Geotechnical Considerations for Design of Soil Nail Walls in Rock Slopes, I-405 Freeway, Sepulveda Pass, Los Angeles, California

Gates, W.C.B.
Kleinfelder, Redmond, Washington, USA

ABSTRACT
I-405 freeway in Southern California is one of the most congested freeways in the United States. Because of the traffic congestion, the Los Angeles Metropolitan Transit Authority (MTA) elected to release a design-build contract to widen the freeway. Some of the major improvements included:

Designing and constructing about 4 km (2.5 miles) of soil nail retaining walls up to 25 m (80-feet) high at side hill cuts

Designing and constructing about 3 km (2 miles) of 1:1 side-hill cut slopes in place of soil nail retaining walls

At Sepulveda Pass, I-405 passes through the Santa Monica slate belt and the Modelo Formation consisting of interbedded sandstones and shales. One of the critical geotechnical design parameters required for design of the walls are the Mohr-Coulomb shear strengths of the geo-material. The shear strength parameters for the rock units were based on non-linear curve envelopes using Hoek-Brown Strength Criterion. These values were then converted to a unique set of linear Mohr-Coulomb strengths using the general Hoek-Brown equations and checked by the computer program RocLab by RocScience; and used in the design of each soil nail wall. Intact rock strength, wall height and the Hoek's disturbance factor were the most sensitive parameters in estimating the design Mohr-Coulomb shear strengths.

ARMA 10-259

Influence of Corrosion Rate on the Capacity of Rock Support

Dorion, J.F.
Université Laval, Québec, Québec, Canada

Hadjigeorgiou, J.
University of Toronto, Toronto, Ontario, Canada

Ghali, E.
Université Laval, Québec, Québec, Canada

ABSTRACT
This paper presents the results of on-going investigations in several underground hard rock mines in Canada. Since the summer of 2007 a series of regular site visits was undertaken in order to monitor the performance of support systems. Site visits originally focused on visual assessment of the performance of support systems and collecting failed support elements for subsequent laboratory investigations. Furthermore, water samples were recovered and analyzed. The influence of atmospheric corrosion on the loss of capacity of support systems was also recorded. Underground mine atmosphere is characterised by high humidity, gas from engines and blasting and fine dust particles of different mineralogical composition. The presence of these conditions has an adverse influence on the ability of steel based support systems to withstand corrosion. A field testing program was designed to evaluate the type and rate of corrosion in the encountered underground mining environments using corrosion coupons. Coupons were recovered at regular time intervals and were subsequently tested in the laboratory. Tensile strength tests were performed on corrosion coupons installed in different underground conditions to establish correlations between the observed corrosion rate (mass loss) and reduction of steel strength. This has significant implications on the long term performance of support systems in corrosive mining environments.

ARMA 10-331

Numerical Analysis of Grout Flow and Injection Pressure Affected by JRC and Aperture Size

Ki-Hwan Jeon, Jong-Woo Song, Jae-Joon Song
Department of Energy Resources Engineering, Seoul National University, Seoul, South Korea

Dong-Woo Ryu, Hyung-Mok Kim, Eui-Seob Park
Institute of Geoscience and Mineral Resources, Daejeon, Korea

ABSTRACT
The grout flow through rock mass discontinuities has usually been simulated with a laminar flow. In the laminar flow through a micro-channel, however, the flow is significantly dependent on the roughness of the channel surfaces. The effect of the joint roughness coefficient (JRC) on grout flow is numerically investigated in this study. A computational fluid dynamics (CFD) code – FLUENT was employed and the Herschel-Bulkley model was used to simulate a grout flow. The model can simulate the flow phenomena including all the resistance factors such as roughness and aperture size. For the verification of the numerical model, the velocity profile of cement paste simulated by FLUENT code was compared with the theoretical results calculated by the Bingham fluid flow equation. Results of a grout injection test analyzed by FLUENT was compared with published laboratory experiments. In this work, a grout injection pressure as well as a pressure drop throughout the rock joint channel were computed for the joint which has a mean aperture size ranging from 0.3 mm to 0.9 mm and JRC value ranging from 0 to 20. It was noted that the grout flow is noticeably affected by the JRC when the aperture size of joint channel was 0.3 mm, but the influence of JRC diminished as the aperture size increased to 0.9 mm.

ARMA 10-402

Examination of Shotcrete Liner at Devil's Slide Tunnel Utilizing ASTM 1550 Field Test Results and Back Analysis

Decker, J. B. and Madsen, P.H.
Kiewit Pacific Co., Pacifica, CA, USA

Gall, V.
Gall Zeidler Consultants, LLC, Ashburn, VA, USA

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). In NATM design a flexible initial lining is used to allow some deformation to occur to mobilize the strength of the rock. The initial lining support utilizes fiber reinforced shotcrete (FRS). The ASTM 1550 Round Determinate Panel Test "Pizza Test" is being conducted on site to ensure the flexural properties or post-crack performance of the FRS. However, the ASTM 1550 does not analyze shear failure due to ground loads imposed on the liner. Therefore, it must be coupled with typical compressive strength testing. Furthermore, measured convergence during excavation presents the opportunity to back calculate and analyze the in situ loading of the FRS liner for a better understanding of its actual performance. In this paper, the to date results of the ASTM 1550 field test program along with a back analysis based on measured convergence to determine the loading of the FRS initial lining will be presented. A brief discussion of the ASTM 1550 testing and the back calculated in situ loading of the liner and how these demonstrate the overall performance of the FRS liner at the Devil's Slide Tunnel will be given.

SESSION 28 — UNCONSOLIDATED FORMATIONS

ARMA 10-219

Use of Volumetric Sand Production Tool on Field Data to help plan Oil Production Strategy

Cerasi, P. R.
SINTEF Petroleum Research, Trondheim, Norway

Berntsen, A.N. and Stenebråten, J.F.
SINTEF Petroleum Research, Trondheim, Norway

Papamichos, E.
Aristotle University and SINTEF Petroleum Research, Thessaloniki, Greece

ABSTRACT
A volumetric sand production prediction tool has been developed, targeting rapid evaluation of production strategies for fields where sand risk may be an issue. The tool incorporates a semi-analytical model, based on hollow cylinder laboratory tests with radial flow where sand mass is monitored as a function of confining stress, borehole deformation and flow rate. Field data has been used as input to this tool in studies were different production strategies were evaluated as to their effect on predicted amount of produced sand. In particular, drilling and completion strategies are easily compared in terms of their associated sand risk: well deviation and perforation pattern. Similarly, the user can easily change input of hydrocarbon production strategy in terms of planned drawdown levels against assumed depletion evolution. Since geomechanical and petrophysical parameters are input as logs, the producing intervals of a whole well can be treated in one run, yielding a sand risk log as output.

ARMA 10-262

Experimental Analysis of Gravel Pack Mesh Size Effect on the Screen Deformation under High in Situ Stress Contrast

Villarroel, F.M.G., Vargas Junior, E.A.
Catholic University of Rio de Janeiro – PUC, Rio de Janeiro/RJ, Brazil

Bloch, M.
Petrobras/CENPES, Rio de Janeiro/RJ, Brazil

ABSTRACT
Whenever designing gravel pack for deepwater oil wells, where it is not possible to repair operational problems without very high costs, one should take into account the needs for a longer term operation, being more conservative in the gravel size selection. A gravel pack prototype was built and installed in a large poliaxial frame for mechanically testing the two most common mesh sizes: 16/20 and 20/40, in order to check on the influence of the gravel size under high in situ stress

contrast. The gravel pack was set on artificial cubic rock samples of 11.8 in side with a centered hole of 2.4 in diameter. The block was then compressed by hydraulic actuators in two perpendicular orientations. Visible screen damage was observed when testing the gravel agent of 16/20 mesh, as compared to the 20/40 mesh, under the same stress field, indicating that smaller particles size are better, regarding equipment integrity (one should always expect permeability reduction with smaller particles in the pack). As a conclusion of the realized tests, in association to the usual requirements for sand control with gravel packs, it is recommended the utilization of 20/40 mesh, instead of 16/20 mesh, for gravel pack installation in deepwater oil wells, at depths with high in situ stress contrast, in order to improve equipment operational life.

ARMA 10-340

Sand Production Rate under Multiphase Flow and Water Breakthrough

Papamichos, E.
Aristotle University of Thessaloniki and SINTEF Petroleum Research, Thessaloniki, Greece

Cerasi, P., Stenebråten, J.F., Berntsen, A.N. & Ojala, I.
SINTEF Petroleum Research, Trondheim, Norway

Vardoulakis, I.
National Technical University of Athens, Greece

Brignoli, M.
Eni, Milan, Italy

Fuh, G-F.
ConocoPhillips, Houston, TX, USA

Han, G.
Hess, Houston, TX, USA

Nadeem, A.
BG, Reading, UK

Ray, P.
Chevron, Houston, TX, USA

Wold, S.
Det Norske, Trondheim, Norway

ABSTRACT
The sand production rate in three outcrop sandstones under various saturation and flow fluids is investigated to reveal the potential contribution of three different mechanisms on sand production rate and initiation. The mechanisms that are investigated are strength water weakening, capillary cohesion in the failed zone and the pore pressure gradient front during water breakthrough. The sand production experiments are designed such that the relevant importance of each mechanism can be identified. Thus for each sandstone four sand production test types are performed and compared. Two of the test types are with one-phase flow and two are with two-phase flow including water breakthrough tests. The three tested sandstones are considered analogues of hydrocarbon reservoirs and represent all three borehole failure classes generalizing thus the applicability of the results which show that all mechanisms are important and have to be considered in the development of relevant sand production quantification models.

ARMA 10-257

Geomechanics of Oil Sands under Injection

David P. Yale, Todd Mayer, Jianlin Wang
ExxonMobil Upstream Research Company

ABSTRACT
Geomechanical properties of heavy oil sands greatly impact our ability to model and implement most heavy oil recovery processes. Many heavy oil recovery processes involve the injection of fluids (or reduction in stresses to allow fluids to

flow) and thus the stress paths during at least part of the process is extensional. This paper investigates the transport and mechanical properties of oil sands under fluid injection and the subsequent stress reduction and dilation that ensues. We find that very significant dilation occurs in the sands during injection and that standard triaxial tests, although showing significant dilation, may not fully represent the stress path and deformation that reservoirs undergo during injection. We find that the interbedded mudstones that are often found in fluvial and tidal depositional environments of Canadian oil sands behave similarly to the bitumen saturated oil sands but with greater amounts of dilation over similar stress paths. We also find that permeability to water of both the oil sands and mudstones increases dramatically along these extensional stress paths.

ARMA 10-117

Chemo-Plasticity Modeling of Pore-Fluid Induced Degradation of Soft Rocks

Marte Gutierrez.
Colorado School of Mines, Golden, CO 80401, USA

Randall Hickman.
BP America, Inc., Houston, TX 77079, USA

ABSTRACT
Porous reservoir rocks, particularly chalk, are known to behave differently when saturated with different pore fluids. The mechanical behavior of these rocks varies with different pore fluid composition and additional deformation occurs when the pore fluid composition changes. In this paper, we review the evidence that behavior of porous rocks is pore fluid dependent, and present a constitutive model for pore fluid dependent porous rocks. Our review indicates that theories of Unsaturated Soil Mechanics (USM) are not fully applicable to the modeling of the effects of pore fluid composition on soft rocks such as chalk. Instead of using USM, the paper proposes a model that is based on chemo-plasticity whereby the material response is dependent on the pore-fluid composition, and the material can degrade with changes in pore-fluid composition. Three degradation matrices are introduced namely: the elastic, elastoplastic and viscoplastic degradation matrices, to model, respectively, the reduced elastic stiffness, reduced shear strength, and the lower pore collapse strength and accelerated timedependent deformation of soft rocks due to changes in pore-fluid composition. Comparisons of model predictions with published experimental data indicate that the model is capable of reproducing observed behavior of chalk under a variety of loading and pore fluid conditions.

SESSION 29 — MONITORING AND REMOTE SENSING

ARMA 10-280

Detection of Surface Deformation at Mining and Geothermal Sites Using Satellite Radar Interferometry (InSAR)

Eneva, M.
Imageair Inc., San Diego, California, United States

ABSTRACT
Satellite radar interferometry is a cost-effective tool using synthetic aperture radar (SAR) data to detect surface deformation over large areas. Two InSAR techniques were applied in three mining areas and one geothermal field. The first technique, differential InSAR (DInSAR), works well in non-vegetated areas and can detect sub-centimeter deformation between two satellite passages with millimeter precision. The second technique, PS interferometry (PSI), is based on the use of "permanent" or "persistent" scatterers, and can work in vegetated areas. It makes use of time series of SAR scenes, providing estimates of deformation rates at the PS locations. The three mining sites are a South African gold mine, a Polish copper mine, and a U.S. coal mine, for which the DInSAR technique has detected subsidence from 2-3 cm to 24 cm, over various time intervals. The use of PSI is demonstrated at the Salton Sea geothermal field in southern California, an agricultural area, where DInSAR does not work. Deformation rates of up to 3 cm/yr were detected at the PS points, associated with both subsidence and horizontal movements. The results show that the InSAR approach is highly effective and precise. It is thus recommended for routine monitoring of surface deformation.

ARMA 10-410

A Photogrammetric Approach to Brittle Fracture Characterization in Mine Pillars

Styles, T. D., Zhang, Y. and Stead, D.
Engineering Geology and Resource Geotechnics Group, Simon Fraser University, Burnaby, BC, Canada

Elmo, D. and Roberts, D.
Golder Associates Ltd., Burnaby, BC, Canada

Yanske, T.
Doe Run Company, Viburnum, Missouri, USA

ABSTRACT
Considerable research has been undertaken in recent years on the brittle fracture modeling of underground mine pillars. To date, however, the characterization of pillars has largely focused on the production of discrete fracture mapping by conventional pillar mapping and the development of empirical pillar damage classifications. Photogrammetry in a room and pillar mine offers an extremely flexible technique for characterizing not only discrete fracture networks but also to investigate ongoing brittle fracture processes associated with pillar damage. This paper describes a photogrammetric study of six pillars within two room and pillar lead mines. Previous work at these mines has developed a pillar damage rating system, which has been successfully used in conjunction with non-linear boundary element modeling in mine design. The authors describe the use of photogrammetry to characterize in detail the pillar damage process emphasizing the geometry and development o intact pillar fractures, step-paths and the importance of rock bridges. The nature of joint and intact fracture bounded debris from pillar spalling is also examined. Photogrammetry of the four sides of the pillars and the production of three dimensional pillar models allows a new insight into the continuity of both natural and stress induced fractures across pillars.

ARMA 10-457

Cell to Node Projections: An Assessment of Error

Goumiri, I. R. & Prévost, J.H.
Princeton University, Princeton, USA

ABSTRACT:
Reservoir simulators typically use cell centered finite volume schemes and do not model directly the coupling of the flow processes with the geomechanics. Introducing fully coupled geomechanical effects in those simulators creates difficulties in interfacing cell variables with nodal variables. Uncoupled or loosely coupled models are used by many researchers/practitioners. These methods require projection of the reservoir cell variables onto the nodes of the geomechanics Galerkin finite element mesh. In this note we attempt to quantify the errors associated with cell to node projection operations. After bounding and analyzing the magnitude of these errors, we conclude that, in general, cell to node projection operations lead to substantial errors.

ARMA 10-367

Fiber Optic Strain and Temperature Monitoring in Crystalline Rock at the Sanford Underground Science and Engineering Laboratory (Susel), Lead, South Dakota

Gage, J. R.
University of Wisconsin – Madison, Department of Geoscience, Madison, Wisconsin, USA

Noni, N.
Montana Tech, Department of Geological Engineering, Butte, Montana, USA

Turner, A.
Micron Optics Inc., Western Region, Houston, Texas, USA

MacLaughlin, M.
Montana Tech, Department of Geological Engineering, Butte, Montana, USA

Wang, H. F.
University of Wisconsin – Madison, Department of Geoscience, Wisconsin, USA

ABSTRACT
We are monitoring temperature and rock deformation at the 4100' level of the Sanford Underground Science and Engineering Laboratory (SUSEL) in Lead, SD. In July 2009, we installed six Micron Optics Inc. OS3600 temperature compensated Fiber Bragg Grating (FBG) strain gages. Strain and temperature data has been collected continuously at one-minute intervals since October 1, 2009. Initial results show that strain data from sensors mounted on the rock surface correlate with changes in air temperature within the mine. In order to isolate the mechanical strain signal, we use a least squares linear thermal expansion analysis to fit the temperature and strain data. The least squares analysis is a reasonable first pass method for separating the thermal effects from mechanical strain. For temperatures below ~35.5 °C there is a good linear fit between strain and temperature, which produces a coefficient of thermal expansion of ~16 x 10-6/°C. The residual of the least squares analysis represents the mechanical strain. For our sensors located on the 4100' level in SUSEL, there is very little mechanical strain recorded.

ARMA 10-417

Case Study: Measuring Subsidence above Coal Mines Using Differential Interferometric Synthetic Aperture Radar

Donovan, J.
Department of Mining Engineering, University of Utah, Salt Lake City, UT, USA

Ismaya, F.
Department of Mining Engineering, University of Utah, Salt Lake City, UT, USA

ABSTRACT
Subsidence above two active longwall mines located in Utah, Deer Creek and Dugout Canyon, was monitored using differential interferometric synthetic aperture radar. Time-lapsed images acquired over a period of 46, 92, and 132 days by the ALOS PALSAR sensor were used to locate areas of ground movement and to image centimeter-scale displacements associated with mining induced subsidence. Over a period of 132 days DInSAR was used to identify and measure the growth of a subsidence trough over an active longwall panel at Deer Creek. The behavior correlates well with field data collected via a photogrammetric survey. At Dugout Canyon the maximum rate of subsidence at a field monitored point measured using DInSAR was 14 cm per month which compares favorably to the field data rate of 10 cm per month. Measurements made using DInSAR a above a second panel at Dugout Canyon during 2006 and 2007 indicated 18 cm of subsidence, nearly identical to the 20 cm measured via GPS. In both cases DInSAR provided a measurement density of 5000 points per square kilometer (the typical size of a single longwall panel). This case study indicates that DInSAR permits the derivation of high resolution ground surface displacement maps and provides a more rational, statistically significant basis for subsidence monitoring and modeling.

SESSION 30 — STORAGE AND REPOSITORIES I

ARMA 10-162

Risks and Mitigation Problems in a CO2 Injection Project for a Petroleum Onshore Field in Brazil

Mendes, R.A., Costa, A.M., Sousa Jr., L.C. and Pereira, L.C.
Petrobras, Rio de Janeiro, Rio de Janeiro, Brazil

Oliveira, M.F.F.
Tecgraf/PUC-RJ, Rio de Janeiro, Rio de Janeiro, Brazil

ABSTRACT
This work shows the methodology for the analysis of fault reactivation in terms of reservoir depletion and/or reservoir pressurization. During reservoir depletion, the normal effective stresses at the fault plane increase and the fault tends to close. However, in some reservoirs with different pressure levels intercalated by shales of little thickness, the fault can be reactivated by differential pressure. On the other hand, during injection, the normal effective stresses on the fault plane may decrease to zero and under this condition, the fault opens and fluid may migrate to another reservoir with a lower pressure. The fault reactivation process is controlled mainly by the initial state of stresses (vertical and minimum horizontal stresses) and by the fault cohesion and fault friction angle.

ARMA 10-307

A Study of Injection-Induced Mechanical Deformation at the In Salah CO2 Storage Project

Morris, J. P.*, Hao Y., Foxall, W., and McNab, W.
Lawrence Livermore National Laboratory, Livermore, CA, U.S.A.

*Now at Schlumberger Doll Research Center, One Hampshire St, Cambridge, MA, U.S.A

ABSTRACT
Large-scale carbon capture and storage projects involve injecting CO2 into a porous, permeable formation that is overlain by an impermeable "caprock". The In Salah Project (a joint venture of BP, Statoil and Sonatrach) includes a CO2 sequestration effort that has successfully injected millions of tons of CO2 into a deep saline formation close to a producing gas field in Algeria. We have performed detailed simulations of the hydromechanical response in the vicinity of the KB-502 CO2 injector specifically because the morphology of the observed surface deformation differed from that above the other injectors at the field. Associated with the injection, we have simulated the mm-scale uplift of the overburden and compared the results with observed deformation using InSAR data. Our results indicate that the best fit is obtained through a combination of reservoir and fault pressurization (rather than either alone). However, our analysis had to make assumptions regarding the mechanical properties of the faults and the overburden. These results demonstrate that InSAR provides a powerful tool for gaining insight into fluid fate in the subsurface, but also highlight the need for detailed, accurate static geomodels.

ARMA 10-333

Surveillance Modeling and Operational Controls Ensure Integrity of Alaska's Grind and Inject Operations

Zaki, K., Zhai, Z., Marinello, S., Abou-Sayed, A.
Advantek International Corp, Houston, Texas, USA

Bill, M.
ASRC Energy Services, Anchorage, Alaska, USA

Engel, H.
BP, Anchorage, Alaska, USA

ABSTRACT
Alaska's Grind and Inject (GNI) operations represent the longest and largest semi-continuous solids waste slurry injection project worldwide. More significant in the current climate of corporate responsibility is that modeling updates and assurance processes allow procedural updates to maintain efficiency and environmental integrity. The modeling program provides data for injection performance analysis and history matching that leads to better understanding of subsurface dynamics. Operational success is evidenced by unblemished capacity to accept large waste volumes with significant ultimate well disposal potential. This paper addresses injection assurance and waste containment throughout project life. The periodic history match of created subsurface features is a major component of this process. Fracture simulation was carried out to match the subsurface response to slurry batch injection through 8 years of injection. The geomechanical modeling necessary to provide the framework on which the simulation works is described. Stress evolution and thermal effects during batch injection is also illustrated for the GNI environments. The disposal domain development has been inferred from the simulation. The provision of designs, solutions and predictions based on the simulation sensitivity studies is described and the impact of field activities is highlighted. Designs, solutions and predictions are given based on the numerical results and sensitivity study verified by past field observations. The verification and updating of the model developed for the GNI operation is provided by the history matching of wellhead pressures through eight years of injection.

ARMA 10-185

3D Geomechanics in UGS Projects.: A Comprehensive Study in Northern Italy

Castelletto, N., Ferronato, M., Gambolati, G., Janna, C. and Teatini, P.
Dept. of Mathematical Methods and Models for Scientific Applications, Univ. of Padova, Padova, Italy

Marzorati, D. and Cairo, E.
Stogit S.p.A., Crema, Italy

Colombo, D. and Ferretti, A.
Tele-Rilevamento Europa S.r.l. (TRE), Milano, Italy

Bagliani, A. and Mantica, S.
Eni S.p.A. - Divisione E&P, San Donato Milanese, Italy

ABSTRACT
The 3D geomechanical response to seasonal gas storage is investigated for a gas field managed by Stogit. The 1200-m deep reservoir is located in the Po basin, Italy, and a UGS program is under way since 1986 following a 5-year primary production life. The use of: i) a basin-scale geomechanical characterization of the Po basin, ii) a detailed knowledge of the subsurface geology made available by 3D seismic surveys, iii) almost 30-year measurements related to the gas field activities, and iv) an advanced PSInSAR analysis providing the vertical and horizontal West-East displacements of the ground surface above the field from 2003 to 2007, has allowed for the development, setup, and calibration of a representative 3D fluid-dynamical model and a transversally isotropic nonlinear geo-mechanical model. The latter successfully reproduces the largest vertical and horizontal seasonal land displacements, on the range of 8-10 mm and 6-8 mm, respectively, as observed above the reservoir. The model is then used to investigate the ground surface displacements in connection with UGS future programs where the maximum overpressure achieved in the field is planned to be raised to 107% pi and 120% pi, with pi the original in-situ pore pressure.

ARMA 10-230

Study of Geomechanical Effects in Deep Aquifer CO_2 Storage

Tran, David, Nghiem, Kohse, Bruce, Long and Shrivastava, Vijay
Computer Modelling Group Ltd., Calgary, AB, Canada

ABSTRACT
Storage of CO_2 has become an important topic in the past few years. This is because excessive CO_2 in the atmosphere is considered as the main factor responsible for climate change and green house effect. The emission of CO_2 gas is mainly caused by human activities from different sources such as electric power plant, petroleum refinery, transportation and natural gas consumption. Therefore, the increase of CO_2 gas in the atmosphere needs be reduced. Currently, CO_2 storage in deep saline aquifers is an attractive approach that is being studied extensively. Saline aquifers have large volumes that can handle a large amount of CO_2 injection. Furthermore, CO_2 can be easily dissolved in brine. However, the above storage may not be secure if the stress and deformation of the aquifer are not analyzed thoroughly. The main focus of this work is using the coupled code between reservoir flow and geomechanics to study when and where gas leakages may occur through the caprock under different scenarios such as injection methods and orientation of injecting wells. A modified Barton-Bandis model is implemented to compute permeability of fractures that occur in the caprock when its tensile strength is overcome by applied stresses, which then allows free CO_2 to escape from the aquifer. Examples are presented to illustrate the workflow in geomechanical risk mitigation of CO_2 storage. Keywords: normal fracture effective stress, tensile fracture, modified Barton-Bandis model, fracture permeability, coupling mechanism, trapping mechanism, deformation.

SESSION 31 — LABORATORY TESTING

ARMA 10-365

Experimental Study on Shear Strength Recovery of Single Rock Fracture through Slide-Hold-Slide Direct Shear Test and its Modeling

Kishida, K. and Kawaguchi, Y.
Department of Urban Management, Kyoto University, Kyoto, Japan

Nakashima, S.
Yamaguchi University, Ube, Yamaguchi, Japan

Yasuhara, H.
Ehime University, Matsuyama, Ehime, Japan

ABSTRACT
In this paper, slide-hold-slide type direct shear-flow coupling experiments on single rock fracture and its theoretical simulation are performed so as to investigate the effects of long-term load holding on the mechanical and hydro-mechanical properties of rock fractures. From the results, it is confirmed that the shear strength of the mortar replica specimens increases and the permeability decreases during three days of load holding. However, no significant changes are observed for the mechanical or the hydro-mechanical properties of the granite specimen even after twenty days of load holding. Moreover, to reproduce the shear strength recovery during short-time holding, we develop a direct shear model by employing a temporal variation in the dilation that occurs during load holding. The model predictions are in relatively good agreement with the experimental observations in the range of the short-holding period.

ARMA 10-148

Initiation and Growth of a Hydraulic Fracture from a Borehole under Toughness — or Viscosity— Dominated Conditions

Zhang, X., Jeffrey, R. G. and Bunger, A. P.
CSIRO Earth Science and Resource Engineering, Private Bag 10, Clayton South, VIC 3169, Australia

Thiercelin, M.
Schlumberger RTC-Unconventional Gas, 14131 Midway Road, Suite 700, Addison, TX 75001, USA

ABSTRACT
A two-dimensional (2D) model is presented for initiation and growth of one or more hydraulic fractures from a vertical borehole that is aligned with one of the principal stresses. The coupling of fluid flow and rock deformation plays a key role in reorientation and pattern evolution of the multiple fractures formed. The simulation results provide the spatiotemporal variations of injection pressure, fracture trajectory, fracture opening and pressure in the fracture. After fracture initiation, the fracture can rotate as it extends from the borehole until it becomes aligned with the preferred direction for fracture growth under the specified far-field stresses. For fractures that extend in a toughness dominated regime, fracture closure may occur along the portion of the fracture path adjacent to the borehole since for this case the fluid pressure is uniform and cannot attain a locally higher value. Local fracture closure does not typically occur when fluid viscous dissipation is introduced, producing high injection pressures. Initiation of a fracture using a viscous fluid and a higher injection rate is a practical way to reduce near wellbore fracture tortuosity. The results demonstrate that the initiation misalignment angle and the in situ stress magnitudes are also important in their affect on fracture path near the borehole.

ARMA 10-312

The Future of Rock Physics: Imaging and Computing

Amos Nur
Stanford University, Stanford, CA, USA

ABSTRACT
Physical measurements of rock properties on cores, plugs, and cuttings are cumbersome, and often impossible to do or do well. They are also very sparse. However what will be needed in the future - for higher resolution seismic interpretation, reservoir characterization, reservoir simulations and production management - are properties not for 10's of samples but thousands or tens of thousands samples. To achieve such massive data sets we are developing a computational - as opposed to laboratory - rock physics methodology. This methodology consists of obtaining 3D very high resolution (down to 3 nanometers) and very fast (minutes) images of the pore spaces of cores, plugs, or cuttings. The images are used 'as is' to accurately obtain bulk properties very fast (minutes) using codes placed on parallel computers that are accessed via the Internet. Properties obtained include porosity, permeability, capillary pressure, relative perm, electrical conductivity, strength, elastic constants, seismic velocities, grain and pore size distributions, and NMR response. Samples can be cores, plugs, and cuttings. From the images we can also computationally rapidly simulate complex pore scale processes such as fine migration, formation damage, compaction associated with production, CO2, steam, and water injection, diagenetic processes, and chemical reactions in the pore space. Future applications of this technology is obtaining permeability logs from cuttings at the well head in quasi real time, rigorously link logs and rock properties, link log and rock properties to seismic to look away from the borehole. Ultimately this technology should be able to transform and massively expand the impact of both routine and special core analysis as practiced today. As I show in this talk this is especially true for rock types where internal pore architecture is crucial to for improved production: carbonates with micro-porosity, heavy oil/tar sands, tight gas sands, and gas-shales.

ARMA 10-376

Comparisons of 2D Imaging Techniques for Internal Macropore Characterization

Nick Hudyma
University of North Florida, Civil Engineering, Jacksonville, FL, USA

Kevin Johnson
University of Florida, College of Medicine, Jacksonville, FL, USA

Christopher Sherman
University of California at Berkeley, Civil and Environmental Engineering, Berkeley, CA, USA

Mary MacLaughlin
Montana Tech of The University of Montana, Geological Engineering, Butte, MT, USA

ABSTRACT

Traditional medical X-ray imaging, CT scanning, and cross-specimen acoustic tomography (CSAT) were used to visualize the internal structure of macroporous plaster specimens and calculate the total volume of the macropores. The traditional medical imaging and CT scanning produced highly detailed images that could be used to assess the size and shape of the macropores. The CSAT imaging could be used to approximately locate macropores but shapes could not be distinguished. Only CT scanning and CSAT imaging could be used to determine the volume of the macropores. A rigorous procedure which provided very detailed measurements was used to calculate the macropore volume using the CT scans. The volume of the macropores using CSAT imaging depended upon a compression wave velocity cut-off velocity which varied from specimen to specimen. Future plans are already in-place to further develop the CSAT imaging technique to hopefully provide better macoopre shape identification and macropore volume calculation abilities.

ARMA 10-195

Effect of Temperature on Ultrasonic Velocities of Unconsolidated Sandstones Reservoirs during the Sagd Recovery Process

Doan, D.H., Nauroy, J.F., and Baroni, A.
Institut Français du Pétrole, 1-4 Av. du Bois Préau, 92852 Rueil-Malmaison Cedex, France

Delage, P.
Ecole des Ponts ParisTech, 6-8 Av. Blaise Pascal, F-77455 Marne la Vallée Cedex 2, France

Mainguy, M.
TOTAL Office EB-181 CSTJF, Av. Larribau 64018 Pau Cedex, France

ABSTRACT

The steam assisted gravity drainage (SAGD) has been successfully used to enhance the recovery of heavy oil in Western Canada and Eastern Venezuela basins. Pressure and temperature variations during SAGD operations induce complex changes in the elastic properties of the reservoir rock. To study these changes, measurements of ultrasonic wave velocities were performed on both reconstituted samples and natural oil sands samples. Reconstituted samples were made of Fontainebleau sand with a slight cementation formed by a silicate solution. They have a high porosity (about 37 % to 40 %) and a high permeability (about 10-12 m^2). Natural oil sands samples are unconsolidated sandstones extracted from the fluvio-estuarine McMurray Formation in Alberta (Canada). The saturating fluids were heavy oil and glycerol with a strongly temperature dependent viscosity. Tests were carried out at different temperatures (in the range -30°C and 80°C) and at different effective pressures (from 1.2 MPa up to 8 MPa). Experimental results showed that the elastic wave velocities measured are strongly dependent on temperature (mainly through the viscosity) whereas little effect of effective pressure was observed. Velocities decrease with increasing temperature and increase with increasing effective pressure. These effects are mainly due to the variations of the saturating fluids properties. The experimental results were afterwards compared with the Ciz and Shapiro [1] approach, a extension of the poroelastic theory of Biot-Gassmann [2, 3], applied for rock filled with the hightly viscous fluids.

ARMA 10-314

True Triaxial Testing of Castlegate Sandstone

Ingraham, M. D.
Clarkson University, Potsdam, NY, USA

Issen, K.A.
Clarkson University, Potsdam, NY, USA

Holcomb, D.J.
Sandia National Laboratories, Albuquerque, NM, USA

ABSTRACT
Deformation bands in high porosity sandstone are an important geological feature for geologists and petroleum engineers; however, formation of these bands is not fully understood. The theoretical framework for deformation band formation in high porosity geomaterials is well established. It suggests that the intermediate principal stress influences the predicted deformation band type; however, these predictions have yet to be fully validated through experiments. Therefore, this study investigates the influence of the intermediate principal stress on failure and the formation of deformation bands in Castlegate sandstone. Mean stresses for these tests range from 30 to 150 MPa, covering brittle to ductile behavior. Deformation band orientations are measured with external observation as well as through acoustic emission locations. Results of experiments conducted at Lode angles of 30 and 14.5 degrees show trends that qualitatively agree with localization theory. The band angle (between the band normal and maximum compression) decreases with increasing mean stress. For tests at the same mean stress, band angle decreases with increasing Lode angle.

SESSION 32 — PERMEABILITY AND FAILURE IN CARBONATES AND HYDRATES

ARMA 10-291

Effects of Self-Preservation of Natural Gas-Hydrates

Makogon, Y.F, and Ghassemi, A.
Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, TX, USA

ABSTRACT
Exploration and economic development of natural gas-hydrate (NGH) deposits as an unconventional energy source requires understanding their conditions of formation and stability in porous media, both on land and offshore, and the fundamental properties of a hydrate-saturated rock. Despite significant investigations within the past forty years, some of the most important insitu properties of hydrates are not well known. This work presents the results of a study of the process of gas hydrate selfpreservation in porous media and its effects on NGH formation and production. The study shows that the self-preservation effect increases the hydrate dissociation temperature by several degrees oC, with the consequence of increasing the energy requirements for hydrate dissociation during gas production from a hydrate deposit by 7-15%.

ARMA 10-471

The Effects of Coupled Chemical-Mechanical Processes on the Evolution of Permeability in a Carbonate Fracture

McGuire, T. P., Elsworth, D.
Department of Energy and Mineral Engineering and G3 Center, Pennsylvania State University, University Park, PA, USA

Karcz, Z. K.
ExxonMobil Upstream Research Company: Integrated Reservoir Performance Prediction Division, Houston TX, USA

ABSTRACT
The quality and producibility of fractured reservoirs is controlled by complex interactions between mechanical and hydraulic properties of both fractures and matrix. Fracture permeability is known to be sensitive to changes in effective stresses and to small changes in the topology of the aperture, which may be modified by coupled mechanical-chemical processes. We examined the evolution of fracture permeability in two carbonate rocks to study the mechanisms that control the effective aperture and the formation of wormholes. Experiments were run on cylindrical cores of Indiana Limestone and Captain Massive Limestone containing a single longitudinal fracture at constant effective confining stress (3.5 MPa) and constant fluid pressure gradient (2.0 MPa per meter of sample). Preliminary results show that rock texture and insoluble content do not significantly affect fracture permeability. On the other hand decreases in confining and effective stresses result in significant decreases in the rates of permeability evolution. Furthermore, our results suggest that using the Damkohler number as a predictor of wormholing in carbonate fractures may not be straightforward, and that the initial roughness of the fracture may have longer term effects on aperture and permeability evolution.

ARMA 10-465

Laboratory Measurements of Static and Dynamic Bulk Moduli in Carbonate

Aiman Bakhorji, Douglas R. Schmitt
University of Alberta, Edmonton, Canada

ABSTRACT
Thirty eight carbonate samples from Arab formation were used in this study. P- and S-wave velocities were measured in all samples on dry and saturated conditions at different confining pressure. The quasi-static strains of the samples under jacketed and unjacketed conditions were measured simultaneously with the ultrasonic measurements on a subset of twenty three of these. Static bulk mduli obtained from quasi-static measurements are lower than moduli calculated from the ultrasonic measurements. These differences can be related to the differences in the strain amplitude between the two measurements. The static-dynamic ratio for high porosity samples scattered around 0.5-0.7, low porosity samples at same pressure the ratio scattered between 0.4 and 0.5. Grain bulk modulus obtained from the unjacketed tests is between 70 to 75 GPa which is close to the bulk modulus of Calcite reported in the literature.

ARMA 10 - 513

Determination of Dynamic Fracture Toughness using CCNBD in SHPB Testing

Ke Man
Institute of Rock Mechanics and Fractals, China University of Mining and Technology, Beijing, China & Rock Mechanics Laboratory, Swiss Federal Institute of Technology, Lausanne, Switzerland

Hongwei Zhou
Institute of Rock Mechanics and Fractals, China University of Mining and Technology, Beijing, China

ABSTRACT
Fracture toughness is a key dynamic fracture parameter. We propose a method to measure the parameter for mode-I fractures in split Hopkinson pressure bar (SHPB) testing with a cracked chevron notched Brazilian disc (CCNBD) specimen. The dynamic fracture toughness is obtained from the peak load given dynamic force equilibrium. The feasibility of this methodology is demonstrated with the SHPB-CCNBD experiments on Mentougou basalt.

ARMA 10-288

Visualizing Oil Displacement in Fractured Carbonate Rocks – Impacts on Oil Recovery at Different Hydrostatic Stress and Wettability Conditions

Fernø, M.A., Haugen, Å. and Graue, A.
Dept. of Physics and Technology, University of Bergen, Bergen, Norway

ABSTRACT
We present laboratory results on oil recovery in fractured carbonate rocks, emphasizing impacts from wettability, the presence of fractures and changes in fracture properties at different hydrostatic stress conditions. The in situ development in water and oil saturations in the matrix and inside the fractures was monitored at oil-wet and water-wet conditions using two visualization techniques. The waterflood oil recovery in a moderately water-wet fractured chalk block was investigated at different hydrostatic stresses and water injection rates, especially looking at the influence of fracture conductivity on recovery efficiency.

ARMA 10-199

Mechanical Behavior of a Brazilian Off-Shore Carbonate Reservoir

Santos, E. S. R. and Ferreira, F. H.
Petrobras Research Center – CENPES, Rio de Janeiro, RJ, Brazil

ABSTRACT
The worldwide oil exploration activities are leading the oil companies to off-shore reservoirs in increasingly more complex environments. The well drilling and reservoir production areas demand deeper rock mechanical knowledge for robust production projects. This article focuses on the mechanical characterization of an off-shore carbonate reservoir by correlation estimates and laboratory testing. The tests include UCS, Brazilian indirect tensile, triaxial and compressibility tests in samples collected from core material out of 3 distinct wells. The results are analyzed in detail to characterize rock strength and to understand how the irreversible rock straining occurs. The available electrical well logs on each cored well allowed the authors to compare the laboratory results against empirical rock strength correlations from the literature. Two elastoplastic rock strength envelopes were fitted to the testing results: the traditional Mohr-Coulomb shear envelope and a two-surface Sandler and Dimaggio envelope. Although the original work of Sandler and Dimaggio was developed for a specific sand material, the perfectly-plastic shear and strain hardening compression cap potentials did present a good overall match of the laboratory observed rock behavior.

SESSION 33 —STORAGE AND REPOSITORIES II

ARMA 10-170

Laboratory Studies of the Compressibility And Permeability of Low-Rank Coal Samples from the Powder River Basin, Wyoming, Usa

Hagin, P.N.
Chevron ETC, San Ramon, California, USA

Zoback, M.D.
Stanford University, Stanford, California, USA

ABSTRACT
We characterize the mechanical properties of coal samples from the Powder River Basin (Wyoming, USA) by conducting laboratory experiments. We present results from laboratory measurements of adsorption, static and dynamic elastic moduli, and permeability as a function of effective stress, pore pressure, and gas species. Notably, we observe that CO2 adsorption causes the static bulk modulus to decrease by a factor of two, while the dynamic bulk modulus remains essentially unchanged. Permeability of both intact and powdered samples decreases by approximately an order of magnitude in the presence of CO2, which is consistent with observations of adsorption-related swelling of the coal matrix. Interestingly, CO2 appears to change the constitutive behavior of coal; Helium saturated samples exhibit elastic behavior, while CO2 saturated samples exhibit viscous, anelastic behavior, as evidenced by creep strain observations.

ARMA 10-332

The Impact of Local Stress Field Orientation on Pressures Encountered during Waste Injection Operations in the Ivan River Field, Alaska

Zaki, K., Marinello, S., Al-Garhy, A., El-Fayoumi, A., Zhai, Z. & Abou-Sayed, A.
Advantek International, Houston, Texas, USA

Simon, G.
Chevron ETC, Houston, TX, USA

Walsh, C., Lynch, M., Greenstein, L. & Hillegeist, T.
Chevron MCABU, Anchorage, Alaska, USA

ABSTRACT
The Ivan River Unit is a remote onshore gas field located in the northwest side of the Cook Inlet basin, in south-central Alaska. Class II drilling and production waste is disposed of onsite. Lack of service roads and accessibility during the winter limit other waste-handling options. Many of the disposal injection wells in the region are recompleted abandoned production wells. Wells that were directionally drilled to production targets may be oriented sub-optimally for injection purposes. Regionally, injection pressures have been low initially, with an increasing trend consistent with the volume of waste injected. It was, therefore, unexpected when unusually high injection pressures were encountered in the Ivan River Unit. The pressures recorded were in excess of the overburden stress and 1400 psi above those predicted in the feasibility study. A geomechanical assessment included a survey of published stress orientation data for the area, which indicated that the principle horizontal stress is oriented sub-perpendicular to the azimuth of the deviated injector wellbore. This orientation would require higher injection pressures due to multiple factors. Primary among these is the higher breakdown pressure required to initiate and propagate a fracture. Limited perforation connectivity can contribute to high frictional pressure losses. The model was benchmarked against the injection history, leakoff and step rate test data provided. An assessment of breakouts in a nearby field confirmed the principle stress orientation and its potential effect on fracture orientation and the resultant injection rates and pressures.

ARMA 10-397

Geomechanical Modeling Techniques Applied to Waste Injection Process

Julio R. Ronderos
M-I SWACO, Houston, TX, USA

Adriana P. Ovalle
IHS CERA, Houston, TX, USA

ABSTRACT
This paper explains the engineering Waste Injection (WI) assurance process and shows examples where its application successfully supports the development of major drilling projects where WI was a critical part of the operation. The methodology followed by the process gives the tools to manage responsible and safely a permanent disposal of the drilling waste while maintaining drilling pace and schedules. The process begins with a full feasibility study FEED where accurate geomechanical modeling is required to define the optimal operational conditions to achieve success during the injection, disposal formation, containment zones, capacity, and operational parameters are defined in the study. The next stage is the calibration of the model with a full injectivity test into the target formation. Once the injection operation begins, monitoring injection and decline pressures allows total control and verification of the injection parameters to maintain control of the waste disposal domain. Injection pressure analysis, during and post injection, determines how the fracture system is behaving as WI progresses. Recalculation of the main geomechanical formation parameters based on the formation pressure response needs to be conducted in order to obtain accurate forecast of the disposal domain and formation capacity. As conclusion, more than 28 MM bbls of waste have been successfully injected worldwide, reducing considerably the impact to the environment compared to conventional disposal options.

ARMA 10-399

Geomechanical Evaluation of Solids Injection

Ivan Gil, Branko Damjanac and Neal Nagel
Itasca Houston, Houston, Texas, USA

Quanxin Guo M-I Swaco
Houston, Texas, USA

ABSTRACT
Subsurface injection disposal often provides a cost effective, environmentally-friendly alternative for the disposal of drill cuttings and other oilfield waste streams. The common disposal lithologies have been low permeability (often nano-Darcy) shale formations, commonly found in North Sea injection operations, or very high permeability, low strength sand formations as represented by the grind-and-inject (GNI) operations on the North Slope of Alaska. A number of disposal scenarios have been proposed for these injection operations including the generation of a „disposal domain for shales or shear dilation and intra-pore storage in weak, high porosity formations. Injection into low-permeability shale was modeled using a 2D Discrete Element Method (DEM) bonded particle model. The model captures the true physics of injection (and repeated injection) into low permeability formations. The modeling results show the potential for the generation of a series of fractures due to repeated injection. In addition, the influence of stress anisotropy, pore pressure and fluid viscosity were also evaluated for their impact on the injection fracturing process.

ARMA 10-380

Sensitivity of Storage Field Performance to Geologic and Cavern Design Parameters in Salt Domes

Park, B. Y. and Ehgartner, B.L.
Sandia National Laboratories, Albuquerque, NM, USA

Herrick, C.G.
Sandia National Laboratories, Carlsbad, NM, USA

ABSTRACT
A sensitivity study was performed utilizing a three dimensional finite element model to assess allowable cavern field sizes in strategic petroleum reserve salt domes. A potential exists for tensile fracturing and dilatancy damage to salt that can compromise the integrity of a cavern field in situations where high extraction ratios exist. The effects of salt creep rate, depth of salt dome top, dome size, caprock thickness, elastic moduli of caprock and surrounding rock, lateral stress ratio of surrounding rock, cavern size, depth of cavern, and number of caverns are examined numerically. As a result, a correlation table between the parameters and the impact on the performance of a storage field was established. In general, slower salt creep rates, deeper depth of salt dome top, larger elastic moduli of caprock and surrounding rock, and a smaller radius of cavern are better for structural performance of the salt dome.

ARMA 10-143

Preliminary Numerical Analyses of Proposed DUSEL Cavities

Loken, M. C. And Brosnahan, A. J.
RESPEC, Rapid City, SD, USA

ABSTRACT
The following paper summarizes the preliminary results of the numerical modeling effort performed in support of the Deep Underground Science and Engineering Laboratory (DUSEL). The investigation was performed to aid in the decision-making process for selection of the final size, shape, depth, and orientation of future DUSEL underground excavations at the Homestake Mine. Specific conclusions of the study reveal host rock may be moderately orthotropic in terms of: (1) in situ stress state, (2) deformational behavior, and (3) strength. Of the three cavity shapes considered (i.e., domed right-circular cylindrical cavity, triaxial ellipsoid, and horseshoe-shaped horizontal prism), the most stable configuration is the domed right-circular cylindrical cavity and the least stable is the horseshoe-shaped horizontal prism. A minimum cavern separation distance of two cavity diameters should be sufficient to limit structural interaction of multiple DUSEL cavities.

SESSION 34 — WELLBORE STABILITY II

ARMA 10-442

A Thermo-Poro-Elastic Analysis of Stress Fields around a Borehole

Wu, B., Zhang, X. and Jeffrey, R. G.
CSIRO Earth Science and Resource Engineering, Clayton, VIC 3168, Australia

ABSTRACT
The mechanical behavior of a borehole in a thermo-poro-elastic medium under non-isotropic far-field tectonic stresses is studied with a focus on the non-isothermal condition. The theory proposed by Coussy (1989) is adopted to account for thermal effects in low-permeability but fractured rocks. By decomposing the problem into axisymmetric and deviatoric loading cases, the analytical solutions in the Laplace space are obtained for each case. Through the numerical Stehfest method, the pore pressure, temperature and stress distributions around the borehole in time and space are obtained. Some conclusions are drawn: first, the pore pressure diffusion has little influence on the temperature, but the thermal effect can change the pore pressure; second, the thermal effect has a strong impact on the distribution of the hoop stresses and strong cooling, around the borehole for example, leads to an more tensile tangential stress; third, the deviatoric loading has little effect on the temperature distribution. Based on these results, a new criterion is developed to predict the breakdown pressure in the presence of temperature variations.

ARMA 10-214

Specialist Program for Injection Pressure Limits ConsideringFault Reactivation Criteria

Pereira, L.C., Costa, A.M., Sousa Jr., L.C., Amaral, C.S. and Souza, A.L.S.
PETROBRAS Petróleo Brasileiro S.A., Rio de Janeiro, Rio de Janeiro, Brazil

Falcão, F.O.L., Portella, F.A., Silva, L.C.F., Mendes, R.A. and Chaves, R.A.P.
PETROBRAS Petróleo Brasileiro S.A., Rio de Janeiro, Rio de Janeiro, Brazil

Roehl, D. and Oliveira, M.F.
Pontiff Catholic University, Rio de Janeiro, Rio de Janeiro, Brazil

ABSTRACT
Numerical modelling of fault reactivation is a complex subject which is studied by different areas as geophysics, geology, civil and reservoir engineering. During fluid production and injection, changes in stress have a significant influence on reservoir behavior. Fault sealing is one of the key factors that control hydrocarbon accumulations. If these faults are reactivated, their permeabilities will likely increase, facilitating fluid migration and potentially compromising the hydraulic integrity of the caprocks that seal the reservoir. Therefore, during a waterflooding process, it is necessary to limit the injection pressure in order to avoid fault reactivation. This limited pressure is calculated using the geomechanical influence on the reservoir behaviour, for which, it is necessary a coupled model with constitutive laws, mechanical properties of the reservoir and surrounding rocks, state of stress etc. On the other hand, the uncertainties inherent to the mechanical properties are huge. To properly characterize a rock, lab tests are necessary, but cores are rarely available for destructive tests. Another solution is to use correlations between seismic response and rock properties. But, how reasonable and accurate are such correlations? This work presents a methodology of fault reactivation numerical modeling considering a sensitivity and probabilistic approach of geomechanical parameters. More than 18.000 simulations with in-house finite element software (AEEPECD®) were carried out to create a robust database. The specialist program was developed using VBA and has the goal to supply an initial estimative for injection pressure limits considering the methodology presented here.

ARMA 10-357

A Methodology of Root Cause Analysis of Well Bore Failure and Lost Production Using the Well Information

Hayatdavoudi, A.
University of Louisiana at Lafayette, Lafayette, Louisiana, USA

Rahmatian, M.
Core Mieralogy, Inc, Lafayette, Louisiana, USA

ABSTRACT
While producing an oil and gas well, the Gulf Coast operators often lose production suddenly due to well bore failure. They often ask us to find the root-cause of lost production using the available well information instead of conducting a sophisticated rock failure modeling. In addition, the operators ask us to recommend a simple remedial completion in order to resume production. In this paper, we present a systematic approach to the problem of a well drilled in waters off Louisiana Gulf Coast to depths below 15000 ft. Following our methodology, for a case presented to us, we analyzed the following:

(1) the formation rock material plugging the production choke and tubing, (2) the Well Logs, (3) the Cement Bond Log and the Variable Density Log, (4) the schematic of Primary Completion, and (5) the Well Production Decline. The results of our work lead us to conclude that the chain of events in this case begins with (a) high draw-down that leads to high rate of water coning or water encroachment upward (b) lack of cement bond allows the water into the producing perforations, (c) subsidence of formation begins with high rate of oil and gas production, (d) highly plastic shale from over pressured, underconsolidated seal above the perforations begins to move downward, and finally (e) the tubing fills up with shale and rock fragments and (f) the production is lost. Equipped with this analysis, we have recommended the following remedial completion: (1) squeezing cement in cavernous cavities in the failed perforations, (2) selectively re perforating suitable zones with good cement support, and (3) calculating the shear stress for a safe drawdown equivalent to or lower than the shear strength of the least shear resistance material, that is, the shale seal above the pay zone. In short, the shale control rather than sand control in deep formations is the key to a successful re-completion.

ARMA 10-407

Abnormal Pore Pressure Mechanisms in Brazil

Freire, H. L.V. and Falcão, J.L.
PETROBRAS, Rio de Janeiro, Rio de Janeiro,Brasil

Silva, C.F. and Barghigiani, L.M.
PUC-RJ, Rio de Janeiro, Rio de Janeiro,Brasil

ABSTRACT:
During the planning phase of an exploratory well, the evaluation of geopressures is used to set the depth of casing shoes and to avoid operational problems during the execution phase such as: wellbore stability, circulation losses, stuck pipe, kicks and blowouts, among others. The main mechanism of abnormal pore pressure generation in sedimentary basins is undercompaction, due to loss of balance during the expulsion of the pore fluids during the compaction process. This may happen in situations where the remaining fluids have no migration options due to the presence of impermeable rocks. The secondary mechanisms of abnormal pore pressure generation may also be present and impossible to quatify. Amongst these mechanisms, we can identify: tectonics, salt dome intrusions, high temperatures, etc. High Pressure High Temperature (HPHT) wells are a class of wells that present a bottom hole temperature (BHT) equal or higher than 300°F (150°C) and bottom hole pressures (BHP) above 10,000 psi or pressure gradient over 0.8 psi/ft (2.6 psi/m). The lateral pressure transfer is another abnormal pore pressure generation mechanism, in which the migration of pore fluids may occur due to geometric elevation difference within the same layer, or the presence of a connecting geological fault. This paper presents a study of an area where the overpressure can be generated by all four mechanisms. The post mortem analysis of the drilling of four HP and HT wells in the southeast of Brazil will provide data to identify the contribution of the primary and secondary mechanisms to the levels of pore pressure found.

ARMA 10-398

Long Term Well Integrity: A Semi-Analytical Approach

Musso, G.
Politecnico di Torino, Torino, Italy

Topini, C. and Capasso, G.
eni e&p, San Donato Milanese, Italy

ABSTRACT
The development plan of a hydrocarbon field includes the design of all the wells forecasted for each productive scenario considered. From a mechanical point of view, the standard design of the completion system is usually done considering those actions expected to develop during the completion phases. However, strains developing in the rock formation in the near wellbore area due to hydrocarbon production, can induce additional mechanical actions on the well structure. The resulting stress regime may cause damage in the well with a consequent reduction of the production rate and, eventually, the loss of it. Since this phenomenon has been identified as a critical issue for compacting reservoirs, this paper presents a simplified one dimensional semianalytical method for the evaluation of the stresses arising in the completion system. Transfer functions have been used to reproduce the relationship between the relative displacement of the structure with respect to the rock formation and shear stresses at the interface. As a final result, the method predicts vertical profiles of displacements and axial loads arising along the well column at different time stages, in accordance with the expected rock compaction, allowing for the assessment of the long term well integrity.

ARMA 10-228

A Three-Dimensional Thermo-Poro-Mechanical Finite Element Analysis of a Wellbore on Damage Evolution

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

ABSTRACT
Stress and permeability variations around a wellbore and in the reservoir are of much interest in petroleum and geothermal reservoir development. Water injection causes large changes in pore pressure, temperature, and stress in hot reservoirs that in turn impact rock permeability. In this paper, two- and three-dimensional finite element methods are developed for thermoporo- mechanical coupled reservoir simulation with damage mechanics and stress dependent permeability. Convective heat transfer is considered to reflect the influence of increased fluid velocity in the damage phase of rock deformation. Damage mechanics is applied to capture the alteration of elastic modulus due to the crack initiation, micro-void growth and fracture propagation. Results show effective stress relaxation in the damage phase and its concentration at the interface between the damaged phase and the intact rock. The models presented promise to be effective tools for the analysis of stress induced micro-seismicity and fracture propagation in geothermal and petroleum reservoirs.

ARMA 10-172

Rethinking of Shale Swelling Based on Interesting Test Results

Hong (Max) Wang
Halliburton, Houston, Texas, USA

ABSTRACT
Shale is troublesome for drilling. This is true partially due to its swelling characteristics when interacting with water. However, shale swelling is a complicated matter and how shale swells is still not crystal clear to many engineers who deal with wellbore instability issues daily. A simplified shale model has been built with equilibrium between osmotic pressure and normal stress acting on the clay platelets by ignoring insignificant factors under practical drilling conditions. This new model reveals that there are two distinct water bodies in swelling shale. Changing stress on the platelets will change the water distribution and their water activities in these two water bodies. This model can explain observed stress sensitive activity phenomena reported on swelling shale. The model provides a quantitative way to predict water activities for shale and a new and important equation for improving wellbore stability analysis. With the model many other phenomena such as time-dependent wellbore swelling or tight-hole can be better understood.

SESSION 35 — MULTIDISCIPLINARY GEOMECHANICS

ARMA 10-124

Back analysis of Over-break in a Longhole Open Stope Operation using Non-linear Elasto-Plastic Numerical Modelling

Cepuritis, P. M. and Villaescusa, E.
Western Australian School of Mines, Kalgoorlie, WA, Australian

Beck, D.A.
Beck Arndt Engineering Pty Ltd, Sydney, NSW, Australia

Varden, R.
Barrick Australia, Kalgoorlie, WA, Australia

ABSTRACT
Back analysis of open stope performance is essential in the dilution control process, as an improved understanding of mechanisms allows one to check the validity of any assumptions and refine geotechnical parameters used in the design process. This paper describe the results of a back analysis of over-break geometries, using non-linear elasto-plastic finite element modelling undertaken at Barrick Gold Australia's Kanowna Belle Gold Mine. The entire sequence of bench and

longhole open stopes at the Kanowna Belle mine was modelled. The back analysis study involved analysing hangingwall over-break data from longhole open stopes from a number of key mining blocks. For the numerical modelling exercise, results grids were placed such that various components of velocity and plastic strain could be ascertained into the hangingwall rock mass, with modelling steps calculated at the individual stope's extraction, prior to backfilling. Stochastic analysis of the CMS over-break data, together with the results from the modelling was used to establish global relationships between velocity and plastic strain and marked increases in overbreak. The back analysis results were then used to develop over-break criteria which can be used as a planning tool to estimate probability and volumes of over-break for any future stope design and/or sequencing option.

ARMA 10-181

Full Scale Linear Cutting Test to Study Rotation of Conical Bit

Eunhye Kim.
The Pennsylvania State University, University Park, PA, USA

Jamal Rostami
The Pennsylvania State University, University Park, PA, USA

Chad Swope
Kennametal Inc, Latrobe, PA, USA

ABSTRACT

Conical bits are widely used in various mining and civil construction operations. One of the most distinctive benefits of the conical bits is the increased life time of the bit, which is believed to be due to uniform wear on the bit as it rotates around its axis during the excavation. However, there is no literature on this topic discussing direct measurement of bit rotation. Since this phenomenon is the basis for prolonged life of the bits in any application, it is very important to determine the parameters impacting bit rotation by direct measurement of this parameter to allow for development of proper mechanisms for improving the rotation. This paper, as a follow up to the previous papers on this topic, will discuss full scale linear cutting tests performed at Kennametal testing facilities in Latrobe PA involving direct measurement of bit rotation. Results of experiments will be discussed along with the related calculation and Finite Element Analysis modeling of the bit to evaluate the controlling parameters in bit rotation.

ARMA 10-256

Low Cover Considerations for the Large Tunnels on the North South Bypass Tunnel Project, Brisbane

Funkhouser, M. R.
Golder Associates Inc, Lansing, Michigan, USA

McQueen, L. B.
Golder Associates Pty Ltd, Sydney, New South Wales, Australia

Boultbee, N. L.
Golder Associates Pty Ltd, Brisbane, Queensland, Australia

Humphries, R. W.
Golder Associates Ltd., Squamish, British Columbia, Canada

Carvalho, J. L.
Golder Associates Ltd, Mississauga, Ontario, Canada

Stabler, J.
Leighton Contractors and Baulderstone Hornibrook Bilfinger Berger Joint Venture, Brisbane, Queensland, Australia

ABSTRACT

There are 7 locations where the rock cover is significantly less than the tunnel spans on the CLEM7 Tunnel (formerly known as the North South Bypass Tunnel) in Brisbane, Australia. The twin highway tunnels are each approximately km long with

wide on and off ramps at both ends and at mid-point of the tunnels, two wide underground intersection chambers and several service and utility tunnels. A total of 8,550 m of the tunnels were excavated by two 12.4 m diameter double shield TBMs and the remaining 3,400 m of the main tunnels and the ramps and utility tunnels were excavated by 8 roadheaders. Where the traffic converges from 3 lanes to 2 lanes at both ends of the tunnels, the rock cover varies from about from 0 m to 6 m while the tunnel spans are from 17 m to 13 m. The intersection chambers near the mid-point of the main tunnels are up to 26.5 m wide and at one location have access ramp tunnels passing over them with clearance of less than 3 m locally. Also in this same area, there are cross passages between the main spans where there is less than 15 m of low quality rock cover. Where the main tunnels pass under the Brisbane River, the rock cover is less than 10 m where there is approximately 55 m of head. The rock mass characterization, analyses and rock support designs were initiated and advanced during the tender design stage. Upon award of the design-build project, the analyses and rock support classes were finalized for these particularly critical areas along with the balance of the tunnels. This paper describes the analyses, designs, support and construction methods that were used to construct the tunnels in the different ground conditions where the rock cover is low compared to the wide spans of the tunnels.

ARMA 10-238

Methodology of In-Situ Stress Analysis and its Application to a Pumpedstorage Hydro-Power Station in China

Chenghu Wang[1,2] and Zhengwen Zeng[2]
[1] Institute of Crustal Dynamics, CEA, Beijing, 100085, China

[2] University of North Dakota, Grand Forks, ND, 58202, USA

ABSTRACT
To meet the increasing demand on electric power in Shandong peninsula, China, local government plans to build a pumped-storage hydropower station. To help the engineering design, hydraulic fracturing in-situ stress measurements were conducted in five boreholes during the geotechnical investigation. In the underground facility cavern zone, the measured maximum horizontal stress σH ranges from 9.35 to 17.75 MPa, the minimum horizontal stress σ h is between 5.97 and 9.75 MPa, and the vertical stress σV varies from 9.34 to 11.48 MPa. In the high-pressure, bifurcated pipeline area, σH is between 11.44 and 19.51 MPa, σ h between 7.10 and 13.01 MPa, and σV between 10.66 and 12.39 MPa. The orientation of σH is N66.6~87.6°W. All the measurements indicate a strike slip stress regime. One numerical model of the engineering area was established to represent the major geological engineering features. By applying laboratory and field testing results to the model, continuous stress distribution in the whole engineering area was calculated. The results are consistent with that indicated in the World Stress Map.

ARMA 10-450

The Role of Geomechanics in the Development of an HPHT Field

De Gennaro, S., Schutjens, P., Frumau, M. and Fuery, M.
Shell U.K. Limited, Aberdeen, Scotland, United Kingdom

Ita. J. and Fokker, P.
Shell International Exploration and Production, Rijswijk, Netherlands

ABSTRACT
The success of infill drilling operations in a deep, high-pressure, high-temperature (HPHT) field in the North Sea depends in part on our ability to predict the deformation and stress changes in the reservoir and overburden formations, resulting from hydrocarbon recovery activities and induced reservoir depletion. These changes can lead to several challenges, including, among others, the closure of the mud weight window due to a substantial reduction in the minimum total principal stress or fracture pressure, the loss of well integrity due to a significant liner deformation caused by the re-activation of pre existing geological faults or weak lithology interfaces, and potential sand production problems due to pore collapse caused by critical plastic deformations. This paper focuses on the construction, calibration and application of a geomechanical model as a predictive tool to assist the understanding of a mechanically complex HPHT field. The geomechanical model proved to be a useful tool to explain field measurements and observations, such as the reduced fracture gradient in the overburden and well failures. In addition, it may assist future field development. Examples of operational support include mud-weight prediction for stable wells, location of relatively safe areas to drill (e.g. with low-slip risk), and advice on drawdown and completion design to prevent or mitigate sand production.

ARMA 10-440

A Critical Evaluation of Unconventional Gas Recovery from the Marcellus Shale, Northeastern United States

Lee, Dae Sung.
Petroleum & Marine Research Department, Korea Institute of Geoscience & Mineral Resources, Daejeon, Korea

Herman, Jonathan D.
Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, USA

Elsworth, Derek.
Department of Energy and Mineral Engineering, Pennsylvania State University, University Park, Pennsylvania, USA

ABSTRACT

The Marcellus tight gas shale represents a significant resource within the northeastern United States. It is both a large reserve, with an estimated 30 to 300 TCF of recoverable gas, and is close to some of the largest prospective markets in the country. However, production is fraught with technological obstacles, the most significant of which include prospecting, access by drilling, stimulation and recovery. Prospecting is difficult because viability of the reservoir relies both on the original gas in place and in the ability to access that gas through preexisting fractures that may be developed through stimulation. Drilling is a challenge since drilling costs typically comprise 50% of the cost of the wells and access to the reservoir is improved with horizontal drilling which may access a longer productive zone within the reservoir than cheaper vertical wells. Finally, stimulation methods are necessary to improve gas yields and to reduce the environmental impacts of both consumptive water use and the subsequent problems of safe disposal of fracwater waste. We discuss the challenges involved in the economic recovery of gas from tight gas shales in general and the Marcellus in particular.

ARMA 10-478

Possible Sources of Acoustic Emission Events During Hydraulic Fracturing

Surdi A.A., Ekart D.D., Duran P., and Suarez-Rivera R,
TerraTek, A Schlumberger company

ABSTRACT

Microseismic monitoring during hydraulic fracturing is a relatively new methodology that provides a distinct opportunity for understanding the evolution of fracture geometry during the treatment. Modern computational capabilities make possible to localize these acoustic events almost instantaneously (in real-rime) and also provides a potential opportunity for altering the treatment to control the development of the fracture. For example, if the operator anticipates that the fracture is approaching a water zone, it may take actions to prevent or lower the rate of propagation in the undesirable direction (e.g., by using bridging agents of diverters). Understanding the sources of acoustic emission events during fracturing is of high importance for exercising this potential and for adequate characterization of fracture propagation and final fracture geometry. In this paper we discuss results of controlled laboratory experiments of fracture propagation with acoustic emission monitoring, and use these results to evaluate the relationship between the induced fracture and the acoustic emission events occurring prior, during, and after fracturing (as the rock unloads). Having a simple experimental configuration and strong control of the fracture geometry, allow us in developing a detailed understanding of the process, including localized stress concentrations during loading and unloading, prior to and after fracturing. Results show the presence of considerable amount of microseismic activity prior to and after fracturing, in the neighborhood of the region where the fracture eventually develops. Although these set of events (pre-fracture, fracture and post-fracture) are easily discriminated in time, they are not easily discriminated otherwise. We are currently investigating various ways for separating these via analysis of waveforms (frequency and polarization).

SESSION 36 —COUPLED PROCESSES III

ARMA 10-482

Deformation Response of Coal Mine Slopes – Implications for Slope Hazard Management using Evacuation Based on Slope Monitoring

Harries, N.J. and Cabrejo, A.G.L.
GroundProbe Pty Ltd, Brisbane, Queensland, Australia

ABSTRACT
Rock slope monitoring is an important hazard management technique for dealing with unstable rock slopes in open pit mines. Data is often used to predict locations of rock slope hazards (areas of increased rock slope deformation) and the likelihood of failure (by reviewing the magnitude of deformation and any accelerating trends). This paper reviews an analysis of rock slope deformation in multiple coal mines, using data from ground based radar interferometry systems. The data is aggregated into a database which has allowed the identification of a number of typical ground response patterns, assessment of the deformation rate levels and examined whether slope instability develops into a collapse situation. Rock slope collapse involves a rapid acceleration and gross movement of the slope often involving dilation or fragmentation of the failed slope mass, which can be high consequence events. Management of rock slope collapse using geotechnical monitoring often involves the use of deformation rate alarms, and the analysis has allowed a study into the alarm thresholds used in the coal mining industry.

ARMA 10-246

Development of Permeability Anisotropy during Coalbed Methane Production

Yu Wu
State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, 221008, China & School of Mechanical Engineering, The University of Western Australia, WA, Australia

Jishan Liu
School of Mechanical Engineering, The University of Western Australia, WA, Australia

Derek Elsworth
Department of Energy and Geo-Environmental Engineering, Penn State University, USA

ABSTRACT
Although coal-gas interactions have been comprehensively investigated, prior studies have focused on one or more component processes of effective stress or sorption-induced deformation and for resulting isotropic changes in coal permeability. In our previous work, a general porosity and permeability model was developed to represent both the primary medium (coal matrix) and the secondary medium (fractures) under variable stress conditions. In this study the permeability model is extended to define the evolution of gas sorption-induced permeability anisotropy under the full spectrum of mechanical conditions spanning prescribed in-situ stresses through constrained displacement, and implemented into a fully coupled model for coal deformation, gas flow and transport in the matrix system, and gas flow and transport in the fracture system. Furthermore, the model incorporates a heterogeneous distribution of fractures in coal. The results demonstrate that under the condition of constant reservoir volume the interaction between fracture and matrix is controlled by the sorption-induced strain only, while under stress controlled conditions, the differential stress may elevate the gas sorption-induced coal permeability anisotropy.

ARMA 10-335

Reactive Transport in a Planar Fracture in Hot- and Poroelastic Rock

Rawal C. & Ghassemi A.
Department of Petroleum Engineering, Texas A&M University, College Station, TX, USA

ABSTRACT:
Fracture aperture and fluid flow are affected by poro-thermo-mechanical processes and mineral precipitation/dissolution. In this paper, we study these phenomena by development and application of a three dimensional porothermo- mechanical model with silica dissolution/precipitation effects. The solid mechanics aspect of the problem is treated using a poro- and thermoelastic displacement discontinuity method, while the solute transport and heat transport in the fracture are solved using the finite element method. The single component solute reactivity in the fracture is considered using temperature dependant reaction kinetics. The model is applied to simulate the impact of water circulation on the dynamics of fracture permeability in enhanced geothermal systems. Injecting under-saturated cold geothermal fluid causes large silica mass dissolution in the fracture in a zone that extended towards the extraction well over time, increasing the fracture aperture in this zone. Fluid pressure near the injection well initially increases with injection and aperture reduction in response to leak-off, however, pressure decreases as cooling proceeds. Thermo- and poroealstic stresses are induced in the reservoir matrix that cause secondary fracturing and possibly induce seismicity.

ARMA 10-375

Controls of Permeability on the Mechanical Evolution of Shortening Basins

Foroozan, R. and Elsworth, D.
Pennsylvania State University, Department of Energy and Mineral Engineering, G3 Center and EMS Energy Institute, University Park, Pennsylvania, USA

Flemings, P.B.
University of Texas at Austin, Department of Geological, Austin, Texas, USA

Bilotti, F. and Muhuri, S.
Chevron ETC, Houston, Texas

ABSTRACT
We follow the evolution of faulting in an idealized prismatic basin during lateral shortening as a result of poromechanical interactions. This includes the deformation-induced generation (compaction) and dissipation (hydraulic fracturing) of pore fluid pressures and the resulting natural evolution an underlying decollement and fault structures. Modeling is capable of representing the form of fault structures that may develop within a basin as a result of shortening. Thrust faulting develops as overpressures evolve to trigger failure. A decollement forms within the system at the boundary with the substrate where overpressures drive failure in extension, by hydrofracturing. Failure in the basin overlaying the decollement initiates from these overpressures at the decollement. Where the evolution of permeability with shear strain is artificially suppressed, pervasive shear develops throughout the basin depth as fluid pressures are pegged everywhere to the lithostat. Conversely, where permeability is allowed to increase with shear strain/rupture, faulting first nucleates at the decollement and localizes upwards through the section. Correspondingly, permeability evolution with shear is an important, likely crucial, feedback in promoting localization, as failure is concentrated at the limits of the upward-migrating fault-tip. Elevated pore pressures approaching the lithostat are localized at the hanging wall boundary of the faults. As faults extend, horsts and graben are ultimately isolated, and evolve with distinctive surface topography and separate pore pressure signatures. Horsts have elevated fluid pressures and reduced effective stresses at their core, and graben the converse.

ARMA 10-415

Permeability Evolution of Gas-Infiltrated Coal under Varied Stress Paths

Ghazal Izadi, Shugang Wang, Derek Elsworth
Department of Energy and Mineral Engineering and G3 Center, Pennsylvania State University, University Park, Pennsylvania, USA

Jishan Liu, Yu Wu
School of Mechanical Engineering, University of Western Australia, WA, 6009, Australia

Denis Pone
ConocoPhillips, Bartlesville, Oklahoma, USA.

ABSTRACT
We explore the conundrum of how permeability of coal decreases with swelling-induced sorption of a sorbing gas, such as CO2. We show that for free swelling of an unconstrained homogeneous medium where free swelling scales with gas pressure then porosity must increase as pressure increases. The volume change is in the same sense as volume changes driven by effective stresses and hence permeability must increase with swelling. An alternative model is one where voids within a linear solid are surrounded by a damage zone. In the damage zone the Langmuir swelling coefficient decreases outwards from the wall and the modulus increases outwards from the wall. In each case this is presumed to result from microfracturing-induced damage occurring during formation of the cleats. We use this model to explore anticipated changes in porosity and permeability that accompany gas sorption under conditions of constant applied stress and for increments of applied gas pressure. This model replicates all important aspects of the observed evolution of permeability with pressure. As gas pressure is increased, permeability initially reduces as the material in the wall swells and this swelling is constrained by the far-field modulus. As the peak Langmuir strain is approached, the decrease in permeability halts and permeability increases linearly with pressure. The rate of permeability loss is controlled by crack geometry, the Langmuir swelling coefficient and the void "stiffness" and the rate of permeability increase is controlled by crack geometry and void "stiffness" alone. Correspondingly, this represents a mechanistically plausible model for the evolution of permeability in swelling materials.

ARMA 10-315
Experimental Study of Heterogeneous Water Flow in a Sheared Fracture

Sakaguchi, K.
Graduate school of Environmental studies, Tohoku University, Sendai, Miyagi, Japan

Goto, M.
Nippon Oil Exploration, Minatoku, Tokyo, Japan

Matsuki, K.
Graduate School of Environmental Studies, Tohoku University, Sendai, Miyagi, Japan

ABSTRACT
We developed an experimental system that can be used to conduct a shear-flow test under a constant normal stress using a flat-jack-type true triaxial compressive test apparatus. A shear flow test was carried out on a cubic specimen with a single tensile fracture with this experimental system. A comparison of the results of the numerical experiment and the shear-flow test suggest that the heterogeneity of fracture permeability may be governed by the spatial distribution of large and small apertures, which can form channels. Thus, continuity between localized passes formed by apertures of various sizes can contribute to the appearance of channels, along with merely large passes. The contact regions of the fracture surfaces enlarged and localized with an increase in shear displacement, and the flow of water in the fracture was blocked. Additionally, gouged material that was produced by contact of the fracture surfaces may have affected the fracture permeability.

ARMA 10-452
Cuttings Injection and Monitoring Operations: Cashiriari Gas Field, Peru

Marinello, S.A.
Advantek International, Houston, Texas, USA

Mohamed, I. M.*
Texas A&M University, College Station, Texas, USA *Formerly with Informateks

Hussein, H. and Helmy, N.
Informateks, Cairo, Egypt

El-Fayoumi, A. and Zaki, K.
Advantek International, Houston, Texas, USA

Airoldi, C. and Cassanelli, J. P.
Pluspetrol, Lima, Peru

Pierce, D.
NOV Brandt, Houston, Texas, USA

ABSTRACT

Performance and environmental assurance of cuttings injection programs require monitoring and periodic analysis of injection response. Such programs provide operational oversight and the ability to respond to changes in performance, providing for optimization of operating parameters to minimize potential negative impacts. Cuttings injection was implemented on a remote pad in the Cashiriari Field, located in a nature preserve in Camisea, Peru. CI was recognized as a technically and environmentally acceptable alternative for waste management in a location with extreme environmental sensitivity. Higher than anticipated injection pressures, indicative of regional and local stress regimes, required adjustments in operating parameters and expectations. Performance was contingent on successful inhibition of reactive clays in and around the target zones. Continuous monitoring of closure pressure and other trends associated with batch injection has made performance predictions possible. Monitoring operations have allowed for performance improvement and/or minimization of potential problems. The operation injected over 212,000 bbls of cuttings on the first pad and continues to be successful on the second pad through careful management of batch attributes and adaptation to operating realities. Assurance derived from such programs provides long term operational viability and social acceptance of cuttings injection as a safe means of waste management.