CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: GoldenRocks 2006: The 41st U.S. Rock Mechanics Symposium and 50th Anniversary of the U.S. Rock Mechanics Symposium
Project No. 20.06002.01.332
AI No. 20.06002.01.332.629

DATE/PLACE: June 17–21, 2006
Colorado School of Mines
Golden, Colorado

AUTHOR: Amitava Ghosh
Center for Nuclear Waste Regulatory Analyses (CNWRA)

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BACKGROUND AND PURPOSE OF TRIP:

The U.S. Rock Mechanics Symposium provides an excellent opportunity to exchange knowledge and ideas with other practitioners in the field on current state-of-the-art advances in rock mechanics and rock engineering. The rock mechanics symposium is held annually and attracts researchers from universities, national laboratories, and different organizations, including a significant number of international attendees. Because this year was the 50th anniversary of the U.S. Rock Mechanics Symposium, it attracted many specialists in the field.

The purpose of this trip was to present a paper titled Seismic Responses of Underground Excavations in Jointed Rock Mass and to attend a course on deepwater geomechanics.

SUMMARY OF ACTIVITIES AND PERTINENT POINTS:

The end of World War II created significant demand for raw materials, energy, and transportation systems to sustain rapid growth. Demand for raw materials required the mines to become deeper and more ambitious civil projects. As a result, understanding the mechanical behavior of rock in situ with joints, fractures, and faults posed a major challenge to mining, petroleum, and civil engineers throughout the world. Recognizing this need for a new discipline and formal approach to tackle these problems, the mining engineering departments of the Colorado School of Mines, University of Minnesota, and Pennsylvania State University decided to establish the U.S. Symposium on Rock Mechanics. The First U.S. Symposium on Rock Mechanics was held April 23–25, 1956, at the Colorado School of Mines, Golden, Colorado. On this 50th anniversary of the first symposium, four prominent rock mechanics engineers presented keynote lectures on their views of the progress made in last 50 years.

Keynote Presentations:

- Professor William Hustrulid presented the first lecture, titled Some Thoughts about Mining, Rock Mechanics, and Butterflies. The U.S. Rock Mechanics Symposium started in April 1956 from mining roots. He stated that mining rock mechanics has not significantly advanced through these conferences, as was originally envisioned. There was early recognition of operator participation in the symposiums; however, that objective was not adequately fulfilled by later symposiums. In general, no time is allocated for formal discussions in any recent symposiums and, consequently, it has become difficult to provide practical suggestions for practical problems. Lack of good practical rock mechanics books, with some notable exceptions, is a major obstacle in advancing rock mechanics education, as is lack of research money. He concluded that the approach to advancement of mining rock mechanics should begin with good case studies. Progress can be made by analyzing and learning from actual failures. Because mining rock mechanics engineers are a vanishing breed, knowledge of case studies in the mining industry now generally resides with the consultants, whom he called the "butterflies." Consultants or "butterflies" should publish good case studies for advancement of rock mechanics, especially in the mining area.

- Professor Charles Fairhurst presented the second keynote lecture, Rock Mechanics: 1956–2006—How Far Have We Really Advanced? He presented a more optimistic viewpoint of the progress of rock mechanics, especially in mining in the last 50 years, although he acknowledged a lack of research funding in rock mechanics since the 1980s, with the exception of a few areas such as nuclear waste disposal and geothermal energy, has significantly affected its progress. The geomechanics program at the National Science Foundation has also suffered from a shortage of available research funds. Despite this, there are still some notable advancements in rock mechanics. He cited the progress made in developing and using distinct element codes by Itasca Consulting Group, Inc., as an example. Instead of modeling the rock mass as a continuum medium (with equivalent properties based on some assumptions), these codes allow the rock mass to be modeled in a more realistic way as a discontinuum medium. Application of the particle-based codes allows the rock to be modeled as a particulate medium (simulating gains in the rock) and has given new insight into the fracture formation and propagation processes. It is extremely difficult to develop a shear fracture in a brittle material, such as rock. All fractures at the microlevel probably form as tensile cracks even when subjected to shear loads. Coalescence of several of these microfractures forms a large fracture. Subsequent displacement along the large fractures would develop the shear crack.

- Professor Evert Hoek delivered the third keynote address, 50 Years of Rock Engineering–Developments and Deficiencies. He echoed the cautious optimism of Professor Fairhurst about progress made in the last 50 years. He cited the development of numerical solution schemes as a notable achievement. He also pointed out that inadequacy of input information is one of the most serious deficiencies in rock engineering projects. Developments in analytical capabilities have outpaced the ability of collecting reliable input data. Rock engineers frequently have to gather input information from inadequate literature references or guess. There is no simple solution to this problem because there is not enough money or time to collect this information. Considerable uncertainties exist in the results even if a parametric study was conducted.

This problem is also exacerbated by the fact that there are few good case histories. Academic journals and conferences do a poor job in publishing the good case studies. On the other hand, trade journals and conferences, by their very nature, provide only simplified versions of the case histories. Fear of disclosure of information and litigation also affects the quality of published case studies. Additionally, field engineers and consultants (butterflies) generally do not have the time to record their experiences and are bound by the same constraints. In many cases, they are not good writers to present their experiences in a well thought out article. One possible solution Professor Hoek suggested is the use of the Internet. He expressed caution in filtering good information from the Internet. He concluded that rock engineering challenges have shifted from purely technological to managing and sharing information and experience.

- Professor Richard E. Goodman presented the last keynote lecture, The Important Geological Influences on Rock Slopes, Tunnels, and Foundations in the Context of a Number of Case Studies. He reported that though significant progress has been made in rock exploration, rock fracture characterization, numerical modeling in discontinua, and instrumentation and its interpretation, determination and characterization of a site's geologic composition, structure, and hydrology can still be quite difficult. Although rock discontinuities (e.g., joints, fractures, and faults) are now recognized as vital for design and construction of rock excavation, not all rock mechanics engineers characterize and analyze the effects of three-dimensional block rock masses on the response of the excavations. He presented several case studies where rock discontinuities in three dimensions had significant impacts on excavation failure.

Both Professors Fairhurst and Goodman were made honorary members of the American Rock Mechanics Association in recognition of their contributions to the field of rock mechanics and rock engineering.

There were four concurrent sessions on mining, civil, petroleum, and general rock mechanics. It was not possible to attend every presentation. A brief summary of the presentations attended is given below.

- UDEC Simulation of Triaxial Testing of Lithophysal Tuff—M.C. Christianson, M.P. Board, and D.B. Rigby.

  M.C. Christianson of Itasca Consulting Group, Inc., Minneapolis, Minnesota, presented results from a study to predict the behavior of lithophysal tuff under triaxial loading using the UDEC computer code. It is difficult to conduct standard confined triaxial laboratory tests on lithophysal tuff, the primary horizon for emplacing the majority of the nuclear waste at the potential repository at Yucca Mountain, Nevada, due to the presence of voids. The authors used the UDEC program to perform triaxial tests numerically on simulated lithophysal tuff samples. This supplemented existing information on uniaxial compression tests. The size of the model was 1 m × 1 m [3.3 ft × 3.3 ft]. Rock was modeled as an assemblage of random, irregular, and interconnected blocks, generated using Voronoi tessellation, with a average dimension of 0.017 m [0.7 in]. Results of the numerical experiments are intended to provide guidance on the variability of physical properties of the lithophysal tuff as a function of lithophysal or void porosity. These experimental data can then be used to predict the behavior of the repository drifts. Results of the numerical testing show consistent trends as a function of lithophysal porosity. Peak compressive strength, tensile strength, and Young's modulus decrease with increase of lithophysal porosity. At higher confining pressure, the post-peak response is less brittle. The authors acknowledged that the effects of lithophysal void shape and size on rock properties were not investigated in this study. The voids used in this study are circular with a diameter of 0.09 m [3.6 in], and the UDEC model is plane strain (i.e., the voids are infinitely long in the third dimension). This limitation of the model may underestimate the measured strength. In addition, presence of existing fractures in the lithophysal rock was not accounted for in this study.

- Time Dependent Evolution of the Excavation Damaged Zone Around Underground Openings for Radioactive Wastes Repositories—F.L. Pellet.

  F.L. Pellet of University Joseph Fourier, Grenoble, France, presented a study on the evolution of the damage zone surrounding underground excavation. Long-term behavior of the host rock mass is one of the major issues in underground repositories for nuclear waste. Degradation of the rock properties may lead to the extension of the excavation damage zone around the opening. To predict the extension of the excavation damage zone over time, a viscoplastic model of the rock with a damage parameter was used. Delayed failure of rock has been observed in many underground openings in hard rock such as the Mont Blanc tunnel which crosses the Alps and the Canadian underground research laboratory in the Lac du Bonnet Granite Batholith. A numerical analysis of an existing tunnel where the excavation damage zone was observed and monitored using the finite element code CAST3M developed by the French Atomic Energy Commission was presented. This 100-year old railway tunnel currently houses the research laboratory of the French Institute for Radiological and Nuclear Safety. Results showed that the viscoelastic damage model reasonably predicted the excavation damage zone extension and modification of the stress distribution around the opening.

- Simulations of Underground Structures Subjected to Dynamic Loading using Combined FEM/DEM/SPH Analysis—J.P. Morris and G.I. Block.

  J.P. Morris of Lawrence Livermore National Laboratory, Livermore, California, investigated the effects of explosive and impact loading on underground structures in a jointed rock mass using the Livermore Distinct Element Code computer program. The program was originally developed to simulate tunnels and other structures in jointed rock masses with large numbers of intact polyhedral blocks. However, slip along preexisting joints and fracture of intact blocks can happen when the underground structures in a jointed rock mass are subjected to explosive loads. This requires a combination of continuum and discrete methods to predict the formation and interaction of the fragments produced. Cosserat point theory and cohesive element formulations were incorporated into the current version of the program. These modifications allow simulation of dynamic fracture formation using combined finite element/discrete element methods. Additionally, a smooth particle hydrodynamics capability has been introduced into the Livermore Distinct Element Code program allowing simulation of fluid-structure interaction. Results of a large-scale simulation of an explosive blast impacting an elaborate underground facility were presented. The facility included several tunnel sections and a lift shaft and spanned 60 m [19.7 ft] in each direction. There were approximately 8 million separate polyhedral blocks and approximately 100 million contact elements. A supercomputer with 4,008 Itanium processors was required to analyze the problem. Results showed that non-persistent joints inhibited shear within the surrounding rock mass and significantly increased the load necessary for the tunnel to collapse.

- Seismic Responses of Underground Excavations in Jointed Rock Mass—S.M. Hsiung and A. Ghosh.

  A. Ghosh (CNWRA) presented results from a field study at the Lucky Friday Mine, Idaho, and small-scale modeling experiments conducted at the Southwest Research Institute® to investigate the effects of repeated seismic motions on dynamic behavior of jointed rock mass around underground excavations. Results of the studies show that a threshold level of seismic amplitude appears to exist before significant permanent rock mass deformation occurs and begins to accumulate as cumulative shear displacements along joints. Depending on the state of stress on individual joints and strengths and material properties of both intact rock and joints, progressive accumulation of damage through slippage along the joints tends to weaken the rock mass and leads to instability of the excavations. Therefore, if underground facilities are located in seismically active regions and are expected to experience several episodes of seismic activity during their intended service life, the effects of repeated seismic loads in the design of such facilities need to be considered.

- The Field-Scale Rock Mechanics Laboratory: Estimation of Post-Peak Parameters and Behavior of Fractured Rock Masses—J.J. Crowder, A.L. Coulson, and W.F. Bawden.

  W.F. Bawden, Director of Lassonde Mineral Engineering Program, University of Toronto, Toronto, Ontario, Canada, described a unique hybrid modeling approach used to estimate the three-dimensional mining-induced far-field elastic stresses for incremental advance of a mining face over a 5-year period. For each mining step, the stress on the plane corresponding to the location of *in-situ* instruments was calculated for the non-linear finite element analysis of the drift geometry that included the rock support. Through an iterative back analysis, the post-peak parameters of the fractured rock mass were adjusted until calculated displacements were comparable to those observed from the instruments located at the same location over the same mining steps. Analysis of two regions of the mine indicated that this fractured rock mass behaves in a brittle manner, as post-peak parameters had to be significantly reduced to match the measured displacements. The extent of failure predicted by the models was verified by monitoring and analysis of the spatial distribution of mining-induced seismic events.

- Microseismic Monitoring and Rockbursting Activity at the Campbell Mine, Ontario, Canada—J. Delgado and R. Mercer.

  J. Delgado of Placer Dome Ltd., Campbell Mine, Red Lake, Ontario, Canada, discussed the microseismic monitoring program at the Campbell Mine. Rockburst with a magnitude larger than 2.5 periodically occurs in the Campbell Mine. After reconfiguring and expanding of the original microseismic monitoring system, the mine currently operates one of the largest mine microseismic monitoring systems in the world. The expanded system has substantially improved the quality and quantity of the data acquired. In one area with poor access, long sensor holes {up to 150 m [500 ft]} were used. The management and timely assimilation of larger amounts of acquired data are quite challenging. Currently, the microseismic and macroseismic data are incorporated in a rock mechanics database. The final challenge is how best to use the improved microseismic data to monitor changes in the condition of the rock mass and to improve the understanding of rockburst generation processes.

- A Hybrid Approach to Modeling Blocky Rock Masses Using a Discrete Fracture Network and Finite/Discrete Element Combination—R.J. Pine, J.S. Coggan, Z.N. Flynn, N.T. Ford, and X.P. Gwynn.

  R.J. Pine of Camborne School of Mines, University of Exeter, United Kingdom, presented an approach using a discrete fracture network program, FracMan, to develop a three-dimensional stochastic model of the fractures using mapped data, combined with the finite element-discrete element geomechanical program, ELFEN. Generally, the blocky rock masses are too sparsely jointed to be treated as equivalent continuum media. Consequently, an equivalent continuum approach using rock mass classification schemes with an empirical strength model cannot be used. The authors have used this approach to simulate block caving to examine stresses and deformation at the caving front and for slopes and landslides. To develop the fracture geometry, mapping the outcrops and excavated surface with speed, safety, and accuracy is needed. Use of photogrammetric and laser scanning methods to obtain this information in a variety of projects was discussed.

- Cutting Joint Blocks and Finding Removable Blocks for General Free Surfaces Using 3-D DDA—G-H. Shi.

  G-H. Shi of DDA Company, Belmont, California, described a methodology and an application to cut blocks from statistically generated finite polygons defined by joints in three-dimensional space using the three-dimensional discontinuous deformation analysis program. If the ratio of joint length to joint spacing is less than 10, the rock mass is likely connected and stable. If this joint length ratio is greater than 10, the rock is likely to be blocky, and a search for removable blocks is necessary. He presented an algorithm for identifying all removable blocks along any excavated (e.g., a tunnel) and natural free surfaces. The algorithm works for both cases where the joints are randomly oriented and where distinct joint sets can be observed.

- Screening Level Characterization of Rock Structure in Dam Foundations Derived from Historic Construction Photographs—T.N. Loar.

  T.N. Loar of Montgomery Watson Harza, Denver, Colorado, presented an approach to identify key blocks at an existing dam foundation using old construction photographs. When the majority of the concrete dams were designed and constructed by the United States Bureau of Reclamation, typical analyses did not include identification of key blocks in the foundation or abutments of these dams as a potential failure mode. Recently, the Bureau of Reclamation began identifying existing concrete dams with key blocks in the foundation. Static and dynamic stability analyses are performed to assess the potential risks. Preliminary geologic screening to identify the presence of a key block in the foundation is problematic because the rock mass is typically covered by the existing dam structures and the reservoir itself. Additionally, for a small number of dams, the existing geologic mapping information to adequately characterize the rock mass structure for identification of key blocks either lacks sufficient details, or may not exist.

Consequently, identifying key blocks may have to be based on observation of rock structures and the interpretation based on original construction photographs. If key blocks are identified in the dam foundation, a targeted field-mapping effort can be developed and implemented. A methodology to identify the presence of foundation key blocks was presented. Validity of this method was demonstrated using photo interpretation of the foundation of a variable radius concrete arch dam. Comparison of the stereonets developed by using information from the construction photographs and the field-collected discontinuity data shows the relative accuracy of the orientation measurements extracted from the photos.

- The Initiation of Slip on Frictional Fractures—C.H. Park and A. Bobet.

  C.H. Park of the School of Civil Engineering, Purdue University, West Lafayette, Indiana, presented the results of an ongoing study on slip of rough fractures. Slip along an inclined rough fracture causes initiation and propagation of Mode II cracks. Under pure Mode II loading, a fracture will grow when its energy release rate reaches a critical value, G_{IIC}, which is generally considered a material property. A number of experiments conducted on acrylic, gypsum, and other synthetic frictional materials with a higher unconfined compression strength indicate that G_{IIC} can be considered a material property only when the peak friction angle of the fracture is similar to the residual friction angle. Otherwise, the critical energy release rate increases with normal stress.

- Computational Aspects of Shallow Depth Pillar Layout Design Problems in Tabular Mining—J.A.L. Napier and D.F. Malan.

  J.A.L. Napier of the School of Computational and Applied Mathematics, University of the Witwatersrand, Johannesburg, South Africa, presented a numerical technique to assess deformation of mine pillars. Classically, evaluation of pillar layout stability requires assessing of the global stiffness of the layout with respect to the assumed or measured strength properties of individual pillars. It is important to assess the detailed local deformations especially with irregular-shaped pillars. The authors described a boundary element-based computational tool using higher order triangular or quadrilateral displacement discontinuity elements for evaluating the irregular pillar geometries. Shallow depth influence functions are used in the formulation. The solution efficiency has been improved using a hierarchical computational scheme that adapts to problems comprising general polygonal-shaped elements. Additionally, introduction of higher order (cubic or quartic) elements facilitates assessment of deformation mechanisms near individual pillars in hard rocks, especially local damage and failure associated with geological structures (e.g., weak parting bands or weak layers within the pillars). A case study for designing a pillar design in a shallow-depth platinum mine was presented.

- A New 3D Stability Model for the Design of Non-Vertical Wellbores—A.M. Al-Ajmi and R.W. Zimmerman.

  R.W. Zimmerman of Engineering Geology and Geophysics, Royal Institute of Technology, Stockholm, Sweden, presented an approach to estimate the required mud pressure to prevent instability in inclined boreholes. The Mohr-Coulomb failure criterion is known to be too conservative to estimate the critical mud pressure necessary to maintain a stable wellbore because it ignores the strengthening effect of the intermediate principal stress. The authors presented a new model to estimate the mud pressure necessary to avoid shear failure at the wall of non-vertical boreholes (i.e., the collapse pressure). This model uses a linear elastic and isotropic constitutive law for the stresses and the Mogi-Coulomb criterion to predict the failure. In general, the Mogi-Coulomb criterion estimates that the collapse pressure is similar to that given by the modified Lade criterion in polyaxial stress states and similar to Mohr-Coulomb in triaxial stress states. By comparison, the Drucker-Prager criterion always underestimates the mud weight necessary.

- New Wellbore Strengthening Method for Low Permeability Formations—I.R. Gil and J-C. Roegiers.

  I.R. Gil of GeoMechanics International, Houston, Texas, presented a new approach to strengthen boreholes, especially in formations with low permeability. Different wellbore strengthening techniques have been proposed over the years to increase the fracture gradient (i.e., the pressure necessary to induce fracture) of formations. One prominent method is the stress cage concept (which is very efficient in permeable formations) where the tangential stress around the borehole is increased by inducing and propping open a controlled fracture at the hole wall. This technique is quite ineffective in low-permeability formations. The authors presented a new procedure for developing a stress cage in low-permeability formations, such as, shale. In this method, temperature changes are induced in the formation by the drilling fluid before setting the stress cage to reduce the tangential stress at the borehole wall. The magnitude of this change in temperature depends on the increment in fracture resistance necessary. Thereafter, the stress cage is set up using standard procedures. Fracture growth is expected to stop after the fracture grows outside the low-temperature zone around the borehole. After establishing the stress cage, the formation is allowed to return to its original temperature. This procedure greatly reduces the probability of dislodging the proppants within the fracture because the hydrostatic pressure does not change significantly.

Dr. Ahmed Abou-Sayed of Advantek International was to present a short course. Instead, K. Zaki of Advantek International conducted the course, covering these topics: (I) rock behavior models (elastic, elastoplastic, compaction/dilatancy, rate effects, and creep); (ii) deepwater reservoir geology (geology and structures, considerations of burial history, compartmentalization and faulting); (iii) stresses, loads, and pore pressure (fracture gradients over pressure); (iv) rock properties during exploration, drilling, production, late-life, environmental, and well abandonment; (v) well drilling in shallow and deepwater and salts; (vi) thermal effects, well completion, and sand production; and (vii) waste (drill cuttings and mud) disposal into depleted formation. Much proprietary information was shown. No handouts were provided.

Although the information presented in this course is directly applicable to the oil and gas industries, knowledge gained in some areas, especially response of rock under a given stress field and estimation of material properties through well logs, may be used in disposal of high-level waste underground.

CONCLUSIONS:

This symposium was beneficial because it covered topics in many disciplinary areas related to rock mechanics and rock engineering. In addition, the conference provided an excellent forum for exchanging technical ideas and addressed current progress on challenging issues related to rock mechanics and rock engineering in the U.S. and other countries. Moreover, presentations by four famous rock mechanics practitioners on the progress made in last 50 years were added benefits in attending this 50th anniversary of the First U.S. Rock Mechanics Symposium.

These was no printed proceedings of the conference. Papers presented at this conference are available in a compact disc from the author of this trip report or from the American Rock Mechanics Association through its website.

PROBLEMS ENCOUNTERED:

None.

PENDING ACTIONS:

None.

RECOMMENDATIONS:

Staff should continue to support the Rock Mechanics symposiums (both U.S. Rock Mechanics symposiums to be held during two consecutive years followed by one symposium jointly conducted by the Canadian Rock Mechanics Association and the American Rock Mechanics Association) through active participation and submission of papers.

SIGNATURE AND DATE:

____________________________	____________________
Amitava Ghosh, Staff Engineer Mining, Geotechnical, and Facility Engineering	Date

CONCURRENCE:

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Asadul H. Chowdhury, Manager Mining, Geotechnical, and Facility Engineering	Date
________________________________	___________________
Sitakanta Mohanty, Assistant Director Engineering and Systems Assessment	Date

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SIGNATURE AND DATE:

for A. Ghosh — 7-27-2006

Amitava Ghosh, Staff Engineer — Date

Mining, Geotechnical, and Facility Engineering

CONCURRENCE:

7-27-2006

Asadul H. Chowdhury, Manager — Date

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