# ARMA e-NEWSLETTER
## WINTER 2015

## In this issue






Please note that an inconsistency occurred in the numbering sequence of past issues. The Spring, 2014 (Special Issue) was Issue 12; Fall, 2014 was Issue 13: and this issue (Winter, 2015) is Issue 14.


## ANNOUNCING *THE 2nd SPECIAL ISSUE OF ARMA e-NEWSLETTER*

Based on the reception and positive feedback from ARMA members to the initial Special Issue of the e-Newsletter in May, 2014, the Publications Committee has decided to launch a 2nd Special Issue, entitled:

***"Imaging and Remote Sensing in Rock Mechanics"***

We anticipate publishing this Special Issue in the Spring of 2015.

### Rationale for Topic Selection

In the past decades, rock mechanics and rock engineering have benefited greatly from technological advances. An area worth noting is the application of imaging and remote sensing techniques. These non-destructive non-contact techniques have provided not only valuable insights into the fundamental behaviors of rocks in the laboratory, but also much needed real-time information for hazard assessment and prevention in the field.

The use of digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI) in conjunction with acoustic emission (AE) to investigate the characteristics of fracture initiation and propagation in sandstones, digital reconstruction of the micro-structure of rock samples at rest or under deformation using X-ray computed tomography (CT), and the use of laser diffraction methods for particle or fragment size analysis are only a few examples of using novel imaging techniques for laboratory studies. Visualization of the rock samples on the surface or in the interior allows deformation and failure "to be seen". Furthermore, these techniques also enable us to extend the length scale of interrogation down to the grain and sub-grain scales.

In the field, while borehole and land geophysics logging techniques have been indispensable in understanding rock mass behavior, remote sensing techniques such as LiDAR (Light Detection And Ranging) or satellite-based techniques are becoming popular. Tunneling and slope stability monitoring in large open pit mines or high mountains are some of the applications where these techniques have been useful.

### Call for Contributions

In this special issue, we welcome any contributions related to applying imaging and remote sensing techniques in rock mechanics and rock engineering studies. We hope that this special issue could stimulate our interest in the benefits and limitations of these novel techniques for both research and practice.

Please communicate your intent to submit a "technical note" or a "case study" related to the topic above to bhaimson@wisc.edu, not later than 15 February 2015. Formal submissions should be received by 15 April 15 2015.

We would like to remind you that ARMA e-Newsletter solicits original contributions in the form of Technical Notes (1,000 words plus a few Figures) on basic or applied innovative research or Case Studies (short reports on investigations undertaken in field projects). Manuscripts are reviewed by ARMA Publications Committee. Manuscripts containing commercial advertisements will not be published.

# News Briefs

## News Briefs/Future Events

### Update: 49th US Rock Mechanics/Geomechanics Symposium, June 2015

Registration for the 2015 Symposium opens on 15 January 2015. This annual meeting will be held in the ever-popular San Francisco from 28 June through 1 July 2015. This meeting promises to have both the professional and technical breadth valuable to members, and to afford ample opportunity for enjoyment and interesting times at this location. Forty-eight technical sessions, four keynote addresses, poster sessions, exhibits, workshops, short courses, technical tours, and special events will be presented. See www.armasymposium.org for more information or to complete an online registration.

### Online Course in Reservoir Geomechanics

ARMA Fellow Mark Zoback (Stanford University) is offering a unique opportunity for an online course, starting 31 March, 2015. This course encompasses rock mechanics, structural geology, earthquake seismology and petroleum engineering to address a wide range of geomechanical problems related the exploitation of oil and gas reservoirs. It is a practical course for geoscientists and engineers in the petroleum and geothermal industries, and for research scientists interested in stress measurements and their application to problems of faulting and fluid flow in the crust. For more information and to enroll go to the following URL:
https://class.stanford.edu/courses/EarthSciences/ResGeo202/Spring2015/about

### ISRM 13th Congress in Montreal, May 2015

The ISRM 13th International Congress in Rock Mechanics will be held from 10 to 13 May 2015 in Montreal, Canada. A special feature will be a symposium on "Shale and Rock Mechanics as Applied to Slopes, Tunnels, Mines and Hydrocarbon Extraction," chaired by Herbert Einstein of MIT. The website is http://www.isrm2015.com.

### GeoProc in Salt Lake City, February 2015

The 5th International Conference on Coupled Thermo-Hydro-Mechanical-Chemical (THMC) Processes in Geosystems is slated for 25-27 February 2015. The agenda calls for interesting perspectives on unconventional oil/gas development, improved oil recovery, and geothermal developments. See the website at www.inl.gov/geoproc2015. Or contact John McLennan at jmclennan@egi.utah.edu.

## News Briefs/Past Events

### Injection Induced Seismicity Workshop

In September 2014 a technical workshop was held in Banff, Canada on injection-induced seismicity, co-sponsored by the Society of Exploration Geophysicists, Society of Petroleum Engineers and the American Rock Mechanics Association (ARMA). The program consisted of nearly 50 technical presentations. Recent occurrences of induced seismicity associated with waste injection, hydraulic fracturing and geothermal and gas production and storage were highlighted.

### 6th Brazilian Symposium on Rock Mechanics (SBMR2014)

The SBMR2014 was held in the city of Goiânia, Goiás, Brazil in September, 2014. The Symposium was organized as a Specialized ISRM Conference, and was co-sponsored by ARMA. The technical agenda included the ISRM Soft Rock Commission Meeting, two short courses, a workshop on Rock Mechanics Challenges for Petroleum Engineering and eight parallel sessions. A full-day symposium for young geotechnical engineers was also held. Papers will be available on OnePetro (www.onepetro.org)

# Validating Computer Programs: A Description of the International DECOVALEX Project

*By J. A. Hudson, ARMA Fellow, Chairman of the DECOVALEX Project, Imperial College, London, UK.*

**Summary**

The DECOVALEX Project (DEvelopment of COupled models and their VALidation against EXperiment) has been operating since 1992. Its objective is developing thermo-hydro-mechanical coupled computer modeling in order to provide the necessary support for the design of underground radioactive waste repositories. The Project consists of Benchmark Tests which are synthetic models for comparison of different research teams' computer modeling results (verification), and Test Cases which are simulations of actual physical cases to establish whether the modeling does in fact represent the rock reality (validation). An international consortium of Funding Organizations supports the DECOVALEX work; currently, the following ten Funding Organizations are: BGR/UFZ (Germany), CAS (China), DOE (USA), ENSI (Switzerland), IRSN (France), JAEA (Japan), KAERI (Korea), RWM (UK), NRC (USA) and SURAO (Czech Republic). In this article, the background to the Project is described and the 2011–2015 DECOVALEX modeling tasks are explained; these cover the range of argillaceous, sedimentary and crystalline rocks.

### ISRM Muller Award to Professor Hudson

Following voting by representatives of the 55 constituent countries of the ISRM on 13 October 2014 in Sapporo, Japan, ARMA Fellow Emeritus Professor John A. Hudson of Imperial College London, UK, was declared the recipient of the 7th ISRM Müller Award, in recognition of distinguished contributions to the profession of rock mechanics and rock engineering.

Previous recipients of the Müller Award have been E. Hoek (1991), N.G.W Cook (1995), H.H. Einstein (1999), C. Fairhurst (2003), E.T. Brown (2007) and N.R. Barton (2011).

**Introduction**

Whenever we prepare for a rock-engineering project there are risks associated with site investigation results, the modeling and consequent design, and the construction itself. Of all the different types of rock engineering projects, however, the design of an underground repository for high-level radioactive waste is certainly one the most difficult and it requires the longest design time. This is because of the unique combination of the many features of such a repository, three of which are listed below.

- The over-riding purpose of the repository is to ensure that unacceptable quantities of radionuclides do not escape to the biosphere, i.e., the repository provides a static storage function rather than the active function of other rock engineering projects such as a road or rail tunnel.
- The regulators require that the design life of the repository is of the order of hundreds of thousands of years, as compared to a few days for the area required for the working face of a longwall coal mine or about 100 years for civil rock engineering projects.
- Unlike other rock engineering projects, such as a metro tunnel, a hydroelectric project, or a mine, where there is a defining facility position and often orientation, a repository can be located in a variety of different rock masses, different locations, and at different depths (apart from planning restrictions).

Ensuring that unacceptable quantities of radionuclides do not escape to the biosphere requires extensive research on protective canisters for the waste, significant site investigation at a chosen site to establish how and when such canisters could leak, and how radionuclides could travel through rock fractures to the biosphere. The required very long design life may also require consideration of the effect of not one but several future ice ages (e.g., in Scandinavia) with the associated effects on the groundwater, the rock stress and the fractures. Moreover, the choice of location involves planning conditions and interaction with the general public.

For all these reasons, considerable generic research of the nature described in this article is required to enable convincing repository design. In particular, computer modeling is now used to support most rock engineering project design, but how do we know that the output from the computer modeling has anything to do with reality? Does the computer model contain the required physical processes? Does it contain the idiosyncrasies of the site being modeled? Have the data been input correctly? In this context, the term verification is used to check that two different computer programs provide similar answers to the same input problem; whereas, the term validation is used to check that the output from the computer program does in fact represent the rock reality. Needless to say, although verification studies can be helpful, it is validation that is required to satisfy the regulators.

**The Development of the DECOVALEX Program**

Thus, for both generic and specific radioactive waste repository design, *in situ* experimentation needs to be linked with computer modeling. This is why the DECOVALEX program was initiated in 1992 with the focus on computer modeling of benchmark cases (verification) and simulation of *in situ* experiments (validation). It is essential to verify that the coupled computer programs are operating correctly and to validate that they do indeed represent the rock reality. An international co-operative research project was launched in Stockholm, Sweden, managed by the Swedish Nuclear Power Inspectorate (SKI), for the period of 1992–1995. According to the agreement of the participating parties, including both funding organizations and their research teams, the overall objective of the DECOVALEX project was "to increase the understanding of various thermo-hydro-mechanical (THM) processes of importance for radionuclide release and transport from a repository to the biosphere and how they could be described by mathematical models". (Note that chemistry has since been included for THMC (thermo-hydro-mechanical-chemical) processes.)

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## Hudson "DECOVALEX Project" Continued

The work began with studies of fractured hard rock (because granite had been selected as the host rock by Canada, Finland, France, Japan, Sweden, and the UK, which were six out of the nine original Funding Organizations) There were three BMT (Bench Mark Test) problems and six TC (Test Case) problems. Due to the success of the initial and subsequent research phases, this project, with the acronymic name DECOVALEX has been extended five times over more than two decades. The first DECOVALEX project was named DECOVALEX I and was followed by DECOVALEX II, DECOVALEX III, DECOVALEX-THMC, DECOVALEX-2011 and the present DECOVALEX-2015.

In line with the motivation for the DECOVALEX work, the organization and research work have the following characteristics: simplicity and efficiency of project management; integrated modeling and experiments; aims of understanding and insight; aims also of method (testing and model) development; manageable task scopes; in-depth discussions; flexible agenda; relevance to performance assessment (PA) and safety assessment (SA); good achievements with many scientific publications; and a platform for training young scientists.

The results of this work during the DECOVALEX phases have been published in the international literature. There have been two books: Coupled Thermo-Hydro-Mechanical Processes of Fractured Media; (Stephansson et al., 1996) and Coupled Thermo-Hydro-Mechanical-Chemical Processes in Geosystems: Fundamentals, Modeling, Experiments and Applications; (Stephansson et al., 2004). The work has also been published in four Special Issues of international scientific journals as follows:

- *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.*, 1995; 32(5)
- *Int. J. Rock Mech. Min. Sci.*, 2001; 38 (1)
- *Int. J. Rock Mech. Min. Sci*., 2005; 42 (5 & 6)
- *Environmental Geology*, 2009; 57 (6)
- *Rock Mechanics and Geotechnical Engineering, 2013; 4 (4 & 5).*

Chin-Fu Tsang was the DECOVALEX Chairman for the period 1992–2006; John A. Hudson is the Chairman for the period 2007–2015; and Jens Birkholzer will be the Chairman from 2016 onwards. Lanru Jing has led the Secretariat for the whole duration of the DECOVALEX project. An important feature of the DECOVALEX project, given the extremely long repository design lead time, is that there has been a strong focus on the training of young researchers—with about 40 PhDs having been awarded since 1992 for research on the DECOVALEX tasks.

### Research Work in the Current DECOVALEX Phase: D-2015

The current phase of the DECOVALEX research (D-2015, i.e., the phase that ends in 2015) consists of research work on water flow through a rock mass, the responses of a rock mass and fractures to physical and chemical disturbances, and the effectiveness of sealing rock voids. Most of the work relates to in situ observations and hence to the validation of computer predictions.

Moreover, the ten Funding Organizations from nine countries in the current phase represent significant international research co-operation: BGR/UFZ (Germany), CAS (China), DOE (USA), ENSI (Switzerland), IRSN (France), JAEA (Japan), KAERI (Korea), RWM formerly NDA (UK), NRC (USA) and SURAO formerly RAWRA (Czech Republic).

The DECOVALEX modeling tasks cover the range of argillaceous, sedimentary and crystalline rocks and are comprised of the following tasks:

- Task A: The Sealex In Situ Experiment, Tournemire Site, France
- Task B1: HE-E Heater Test, Mont Terri, Switzerland
- Task B2: EBS Experiment, Horonobe, Japan
- Task C1: THMC of single rock fractures
- Task C2: Water Inflow, Bedrichov Tunnel, Czech Republic

**Task A: The Sealex in situ experiment, Tournemire site, France**

The Task A Test Case involves study of large-diameter bentonite cores and bentonite–rock interfaces with the objective of evaluating the impact of the seals (bentonite and concrete plugs) on the performance and safety assessment functions (Figure 1). The knowledge gained from the experiments will be applicable to other host rocks, such as crystalline and sedimentary rocks (the main instrumented component is bentonite which is needed for repositories in crystalline rocks, such as granite). Also, the experiment has a direct impact on design, implementation, evaluation and monitoring of the sealing systems (bentonite and concrete plug) of geological repositories, especially on the post-closure issues of safety assessment after the sealing system installation in different host rocks, for both near- and far-field safety cases.

Above: Figure 1. Work on the *in situ* experimental studies at the Tournimere site in France.

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The main testing features are: placement of pre-fabricated bentonite cores (seals) into horizontal boreholes (600 mm in diameter) in the wall of galleries of the Underground Research Laboratory (URL); forced saturation of the bentonite cores with watertight sealing of the boreholes; and, intra-core instrumentation with non-disturbing wireless systems installed in the bentonite core to prevent potential preferential fluid flow pathways. The participating research teams are performing numerical simulations of the saturation phase of the Sealex *in situ* tests for different testing conditions and modeling the coupled hydro-mechanical behavior of the bentonite–rock interfaces.

**Task B1: The HE-E in situ heater test, Mont Terri Underground Research Laboratory, Switzerland**

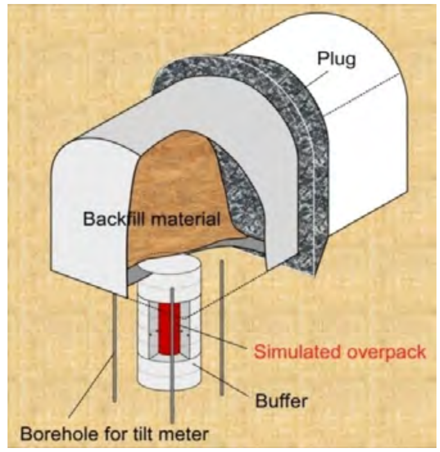
This work, linked to an experiment in the Opalinus clay at the Mont Terri Laboratory in Switzerland, is a Test Case based on the NAGRA PEBS (Long-term Performance of Engineered Barrier Systems) program. (Figure 2.) The objective is the evaluation of the sealing and barrier performance of the EBS (Engineered Barrier System) with time during the heating phase of a repository. Similar to Task A, the knowledge gained from experiments will be applicable to other host rocks, such as crystalline and sedimentary rocks, since the main instrumented component is the EBS (bentonite and concrete plug) which is also needed for repositories in other rocks, such as granite. The work involves a combination of blind prediction, model calibration with measured data, and long-term prediction for performance assessment (PA) and safety assessment (SA) impact evaluation of the EBS.

Right: Figure 2. The research tunnel at the Mont Terri Underground Research Laboratory, Switzerland.

The main scientific issues being considered are the thermal evolution, buffer (bentonite) resaturation process and *in situ* determination of thermal conductivity of the bentonite and its dependency on saturation, pore water pressure evolution in the near-field, swelling pressure evolution of the bentonite, and water input from rock to the EBS. The heating started in 2011 and was continued for a period of three years with a designed heater surface temperature of 135°C. Laboratory tests are also being performed to characterize the behavior and parameters of bentonite blocks, granular bentonite particles and the Opalinus clay rock.

**Task B2: The EBS experiment at Horonobe**

This EBS (Engineered Barrier System) experiment is being conducted in sedimentary rock at the Horonobe Underground Laboratory in Japan with the main instrumented component being bentonite and sand.




Left: Figure 3. The Engineered Barrier System at the Horonobe Underground Research Laboratory in Japan.

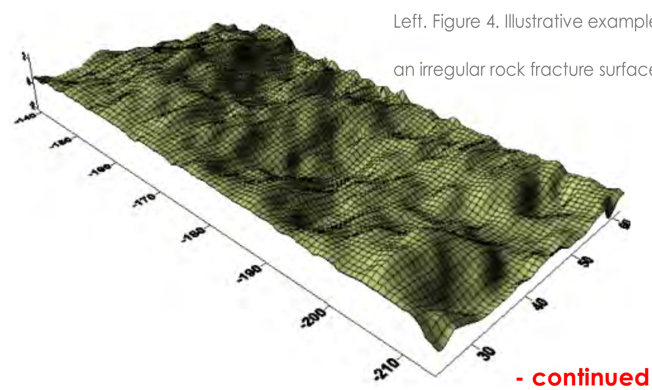
(Figure 3). The objectives of the Test Case are to validate the coupled thermo-hydro-mechanical-chemical (THMC) model and to obtain wider data on an engineered barrier system and the associated THMC phenomena in the surrounding rock. Additional objectives are to confirm both the applicability of the measurement techniques for confirming the performance of an engineered barrier system and the 'set-up technology' of such an engineered barrier system, including the backfill of the tunnel using practical techniques given the in situ environment.

As with the Tasks A and B1, the knowledge gained from the experiments and modeling will be applicable to other host rocks such as crystalline and sedimentary rocks because the main instrumented components are the EBS (bentonite and plug) that are also needed for repositories in crystalline rocks such as granite. The work involves a combination of blind prediction, model calibration with measured data and long-term prediction for the impact of the EBS on PA/SA studies. The scientific issues concerning thermal evolution, buffer (bentonite) resaturation process, backfill effects, pore water pressure evolution in the near-field, swelling pressure evolution of the bentonite, water input from rock to the EBS (involving characterization of rock saturation surrounding the EBS), and possible chemical issues, with model development and validation, and confidence building as one of the major objectives.

**Task C1: THMC modeling of rock fractures**

The work for Task C1 involves the study of laboratory sample-sized rock fractures for understanding and modeling the fully coupled THMC processes as fluids flow through the fractures. (Figure 4.) It is based on data obtained from published papers and can thus be considered as both a Benchmark Test and a Test Case. Fully-coupled THMC processes of a single rock fracture have not been attempted before within the DECOVALEX Project phases but these processes are an issue of dominating importance for the PA/SA of repositories in fractured crystalline rocks such as granite and may also have important reference values for repositories in other types of host rocks.

Left. Figure 4. Illustrative example of an irregular rock fracture surface.



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## Hudson "DECOVALEX Project" Continued

The work is aimed at modeling the fully-coupled THMC processes of rock fractures based on data from the laboratory experiments on novaculite (Yasuhara et al, 2006) and granite (Yasuhara et al, 2011). The overall objective of the Task is to use the experiments to build and refine conceptual and physical process models for the single fracture system and to present this developed understanding in a way that can be useful input for underpinning science in radioactive waste disposal and safety case development.

The novaculite experiment is being studied first, together with considering the impacts of different approaches adopted by the research teams. The work will then move on to consider the granite case based on learning from the fracture surface evolution in the novaculite experiment—through moving from a well hydraulically constrained system (the novaculite) to a less constrained system (the granite).

**Task C2: Modelling water flow into the Bedrichov Tunnel, Czech Republic**

The work for this task involves predicting the water flow into the Bedrichov water transfer tunnel located in the Bohemian granite massif in the Czech Republic. (Figure 5.) The objective is to evaluate the groundwater flow and tracer transport processes at the site scale and compare the result with the recorded data, and to consider the treatment of uncertainties for site characterization. Thus Task C2 is also a Test Case. The experiment and research will assist with the site characterization practices for radioactive waste repositories in crystalline rocks by considering the challenging fracture system characterization issues that play an important role in the reliability and uncertainty issues of PA/SA.

A major advantage of this Task is that considerable work has already been completed in the previous DECOVALEX phase in obtaining the basic information. A comprehensive database is already established containing the available data on site geology, fracture mapping (inside the tunnel), resistivity profiles, water inflow, water chemistry, stable isotope sampling and results, and fracture displacements.

Left: Figure 5. Bedrichov water tunnel in the Czech Republic.

The main scientific issues being considered are:

- hydro-geological characterization of the test site;
- stress measurement and interpretation of results at the site scale;
- groundwater flow and reactive tracer transport study: measurements and numerical modeling, considering discontinuity and heterogeneity issues;
- borehole stability;
- impact of uncertainty of the fracture system geometry and hydro-mechanical behavior on water flow and tracer transport.

The study considers the impacts of fluid flow pathways formed by the rock fracture system, heterogeneity of the rock mass and chemical composition, temperature, tracer mixing, and related water/tracer chemistry.

Further information on the history and current activities of the DECOVALEX program can be found at www.decovalex.org. The author can be reached at john.a.hudson@gmail.com.

### Acknowledgements

The author is grateful to Dr Chin-Fu Tsang (former DECOVALEX Chairman) and Dr Lanru Jing (DECOVALEX Secretary) for their assistance in providing some of the DECOVALEX historical material.

The author appreciates and thanks the DECOVALEX2015 Funding Organizations for their financial and technical support of the DECOVALEX project work described in this article. The statements made in this article are, however, solely those of the author and do not necessarily reflect those of the DECOVALEX Funding Organizations.

### References

ENGGEOL 2009. *Environ. Geol.* 57 (6).

IJRMMS Special Issue. 1995. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr.* 32(5).

IJRMMS Special Issue. 2001 *Int. J. Rock Mech. Min. Sci.* 38 (1).

IJRMMS Special Issue. 2005. *Int. J. Rock Mech. Min. Sci.* 42 (5 & 6).

JRMGE 2013. *J. Rock Mech Geotech. Eng.* 4 (4 & 5).

Stephansson, O., Hudson, J.A. & Jing, L. (eds.) 2004. *Coupled Thermo-Hydro-Mechanical-Chemical Processes in Geosystems*. Elsevier Geo-Engineering Book Series, Elsevier, London.

Stephansson, O., Jing, L. & Tsang C.-F. (eds.) 1996. *Coupled Thermo-Hydro-Mechanical-Processes of Fractured Media*. Developments in Geotechnical Engineering, 79, Elsevier, London.

Yasuhara, H., Polak, A., Mitani, Y., Grader, A., Halleck, P., & Elsworth, D. 2006. Evolution of fracture permeability through fluid-rock reaction under hydrothermal conditions. *Earth Planet Sc. Lett.* 244: 186–200.

Yasuhara, H., Kinoshita, N., Ohfuji, H., Lee, D.S., Nakashima, S., & Kishida, K. 2011. Temporal alteration of fracture permeability in granite under hydrothermal conditions and its interpretation by coupled chemo-mechanical model. *Appl. Geochem.* 26: 2074–2088.

# Mechanics and Rock

By Charles Fairhurst, ARMA Fellow, University of Minnesota and Itasca Consulting Group.

***Author's Note: Part II***

*Part I of these notes, published in the Fall 2014 (Issue 13) issue of the ARMA e-Newsletter,[1] presented examples of where rock mechanics and rock engineering can help address important consequences of the current, rapidly increasing world population and associated rates of change. Such urgent issues as how to alleviate effects of climate change while meeting the increasing global demand for energy, minerals, water and other earth resources were addressed.*

*This concluding segment is developed in three parts:*

- *The need for increased interdisciplinary collaboration in geomechanics*
- *Some current technological issues in rock mechanics*
- *Observations on the state of rock mechanics/mining engineering in the U.S.*

*The purpose of these personal opinions is to stimulate discussion within the American Rock Mechanics Association (ARMA), to address what I believe is a serious situation with respect to the future of Earth Resources Engineering in the nation, and hopefully to arrive at a course of action that will ensure that Earth Resources Engineering (also known as Subsurface Engineering) receives the increased attention that is so urgently needed.*

*Although the comments in this note are a result of valuable interaction and discussions with many colleagues over several decades, I take responsibility for the views and opinions expressed here. I offer my sincere thanks to ARMA colleagues for stimulating me to put these views into writing.*

### *Need for Interdisciplinary Collaboration in Geomechanics*

A recent report, 'Subsurface Characterization,'[2] (September 2014) produced by the JASON[3] group for the US Department of Energy (DOE) notes,

> "Our overarching finding is that in addition to the engineered subsurface being important in several of DOE's[4] mission areas, the science appears ripe for breakthroughs. Disparate research communities working in related areas can benefit from increased coordination (academia, industry, multiple government agencies), and DOE has specific capabilities that can affect these advances. We therefore recommend that DOE take a leadership role in the science and engineering needed for developing engineered subsurface systems."

Recognition of the value of interdisciplinary dialog and collaboration between geoscientists and geoengineers is not new. For example, over two decades ago Scholz (1990)[5] observed,

> "It is a consequence of the way in which science is organized that the scientist[6] is trained by discipline, not by topic, and so interdisciplinary subjects such as this one[7] tend to be attacked in a piecemeal fashion from the vantage of the different specialties that find application in studying it. This is disadvantageous because progress is hindered by lack of communication between the different disciplines, misunderstandings can abound, and different, sometimes conflicting schools of thought can flourish in the relative isolation of separate fields. Workers in one field may be ignorant of relevant facts established in another, or, more likely, be unaware of the skein of evidence that weights the conviction of workers in another field. This leads not only to a neglect of some aspects in considering a question, but also to the quoting of results attributed to another field with greater confidence than workers in that field would themselves maintain.[8] It is not enough to be aware, second hand, of the contributions of another field - one must know the basis, within the internal structure of the evidence and tools of the field, upon which that result is maintained. Only then is one in a position to take the results of all the disciplines and place them, with their proper weight, in the correct position of the overall jigsaw puzzle."

Echoing essentially the same sentiment in his forthcoming book, "Elements of Crustal Geomechanics,"[9] Cornet observes,

> "Today geoengineers and geoscientists dealing with the mechanics of Earth materials must speak the same language."

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[1] http://armarocks.org/wp-content/uploads/2014/10/2014_fall.pdf

[2] Subsurface Characterization (September 2014) JSR -14-Task-013 http://www.energy.gov/sites/prod/files/2014/09/f18/2014%20SubTER%20JASON%20Report_1.pdf. An earlier JASON report on 'Enhanced Geothermal Systems' (Dec.2013) JSR-13-320 identified other subsurface development challenges and opportunities in rock mechanics. http://www1.eere.energy.gov/geothermal/pdfs/jason.final.pdf

[3] An independent group of scientists, advisory to US government. See http://en.wikipedia.org/wiki/JASON_%28advisory_group%29

[4] U.S. Department of Energy

[5] Extract from Scholz, Christopher, H (2002). *The Mechanics of Earthquakes and Faulting*, Cambridge Univ. Press. 471p. Preface to First Edition (1990), reprinted in the Second Edition.

[6] This is true also in engineering.

[7] Although the primary focus of Professor Scholz's book is on *The Mechanics of Earthquakes and Faulting*, his comments apply to rock mechanics in general. As he notes later in his Preface "*…my own specialty is rock mechanics and so this approach is the one most emphasized in this book.*"

[8] The writer (C. Fairhurst), an engineer, may be guilty of this error in interpreting some of the information from other disciplines.

[9] F.H. Cornet. (2015) *Elements of Crustal Geomechanics, ,* Cambridge University Press (in press).

## "Mechanics and Rock" (continued)

It is also worth noting that this need for dialog between geoscientists and engineers was recognized in the United States some four decades ago. The Third ISRM[10] Congress in Denver in 1974 (the only one organized in the U.S.) included 'Tectonophysics' as one of the five plenary themes. Today essentially every U.S. Rock Mechanics Symposium and ISRM Congress is devoted exclusively to engineering issues.

Rock mechanics applications have developed along two distinct and almost independent paths characterized in large part by differences in the scale of the problems, both spatial and temporal.

The engineer must contend with the same geological and tectonic system, albeit on a much smaller scale, up to a few kilometers and the order of a hundred years.[11] Facing the consequences of disturbing a pre-existing equilibrium in the rock mass, the engineer must develop safe solutions to problems such as the violent rock failure induced in deep underground mines;[12,13] surface subsidence due to underground extraction of solids and/or fluids; tunnel and dam construction;[14] reservoir-induced seismicity;[15] stability of deep boreholes; etc.[16] Papers on subsidence and roof control in coal mines were published in the late 19th Century,[17] but activity in rock mechanics increased significantly from the end of World War II, part of a general increase in industrial R&D, i.e., application of science to industrial problems.

Over the same period, geoscientists have given considerable attention to global-scale issues of earthquakes,[18] faulting[19] and earthquake prediction.[20] Both fields of enquiry are concerned with the mechanics of fractures and discontinuities in rock over a wide variety of scales.

The development of nuclear power in the 1950's generated an awareness of another feature of rock *in situ*, its potential as a 'container,'[21] able to isolate long lived high-level radioactive waste (HLW) from the biosphere for periods of many thousands of years. This is an attribute that cannot be demonstrated for any man-made material. Seeking the most suitable geologies and location for these waste 'repositories' increased the scale to that of national boundaries, and required close collaboration between geoscientists and engineers.

The value of this collaboration is illustrated well in the excellent report, "Extreme Ground Motions and Yucca Mountain," (2013).[22] The US Nuclear Regulatory Commission required that the DOE provide a credible estimate of the maximum ground motion that could occur at the site with a probability of $10^{-4}$ over a 10,000-year period (i.e., a probability of $10^{-8}$/yr). Estimates by a panel of leading seismologists predicted a peak ground acceleration (PGA) of 11g and (PGV) of 13 m/sec. Although the panel recognized these values were extreme and physically unrealistic, they were unable to constrain them statistically. Engineers faced with establishing the strength of the volcanic tuff, the host rock for the waste, were able to demonstrate that the lithophysal cavities[23] in the tuff would collapse when subjected to a PGV of the order of 1m/sec. Since the tuff was formed more than 12 million years ago and the lithophysae were intact, this established that the tuff had not experienced any ground motions approaching the values predicted statistically. Such arguments, plus other physical observations, combined to reduce the $10^{-8}$/yr PPV limit to a more credible 4m/s.

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[10] ISRM - International Society for Rock Mechanics

[11] Study of the mechanical properties of rock specimens (i.e., detached from the rock mass) extends over centuries See R.Ulusay (2014) The Present and Future of Rock Testing: pp.1-22 in *ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*.

[12] E. de St Q. Isaacson (1958) *Rock Pressure in Mines,* Mining Publications (London). In South African gold mines. "*…over 69,000 mineworkers had died in the first 93 years of this [20th] century, and more than a million were seriously injured*" http://www.klasslooch.com/leon_commission_of_inquiry.htm The primary cause was rockbursting.

[13] http://conf.gsras.ru/conf/RaSiM8-first-announcement.pdf

[14] J Talobre (1957) La mécanique des roches appliquée aux travaux publics. Dunod (Paris)

[15] UNESCO Conf .*Seismic Phenomena Associated with Large Reservoir Loading* (1973), March 26, 30. Imperial College, London, http://unesdoc.unesco.org/images/0000/000063/006337EB.pdf

[16] Petroleum companies maintain vigorous R&D groups, but much of the work is proprietary.

[17] E.g., References in *Transactions of the Institution of Mining Engineers* (Great Britain), Vol.31, January 1, 1907, « Note sur les Mouvements de Terrain provoqués par l'Exploitation des Mines » by Mr. Henri Fayol, Bulletin de la Société de l'Industrie Minérale, 1885, second series, vol. xiv. p.805. "Effects produced on the Surface by Mine Workings".Henri Fayol, Trans.N.E.Inst.Min.Engrs,1886 vol.xxxv p. 62. Fayol, a graduate of L'Ecole des Mines de St.Etienne, France, later made distinguished contributions to Management Theory [See http://en.wikipedia.org/wiki/Henri_Fayol].

[18] C.F. Richter *Elementary Seismology* (1958) W. H. Freeman & Co (San Francisco).

[19] E.M. Anderson. (1951) *The Dynamics of Faulting and Dyke Formation with Applications to Britain*, Oliver & Boyd, (Edinburgh).

[20] F. Press. (1975) Earthquake Prediction. *Scientific American* ,Vol. 232, No.5. pp.14-23. http://www.scientificamerican.com/article/earthquake-prediction/
L.R. Sykes, B.E. Shaw and C.H Scholz (1997) Rethinking Earthquake Prediction (1997) *Pure Appl. Geophys*. 155 (1999) pp. 207–232
C.H.Scholz (1997) What Ever Happened to Earthquake Prediction? *Geotimes*,Vol.17,March 1997 http://earthquake.usgs.gov/research/parkfield/scholz.html

[21] *The Disposal of Radioactive Waste on Land* (1957) US Nat. Acad. Sci./Nat Res. Council Pub.519 http://www.nap.edu/openbook.php?record_id=10294. The half-life of the radioactive isotope Plutonium (Pu239) a component of HLW is 24,100 years, and may need to be isolated from the biosphere for the order of ten half-lives i.e., as long as Man has been on Earth. Demonstrating that this can be done is a daunting challenge. See also P.A.Witherspoon and G.S. Bodvarsson (2006) *Geological Challenges in Radioactive Waste Isolation* Fourth Worldwide Review. L B N L-5 9 8 0 8 http://esd.lbl.gov/FILES/research/programs/new/lbnl-59808-wwr4.pdf

[22] Hanks, T.C. et al; (2013*) Extreme Ground Motions and Yucca Mountain*. (Final Report) USGS Open File Report 2013-1245 See http://pubs.usgs.gov/of/2013/1245/
Hanks, T.C. (2004) *Report of the Workshop on Extreme Ground Motions at Yucca Mountain*, August 23-25, 2004, U.S. Geological Survey, USGS Open-File Report 2006-1277. T. C. Hanks et al., Eds. Reston, Virginia: USGS, 2006. http://pubs.usgs.gov/of/2006/1277/of2006-1277.pdf

[23] http://en.wikipedia.org/wiki/Lithophysa

Another example of such collaboration, also associated with nuclear issues, is provided in the report, "Underground Nuclear Testing in French Polynesia: Stability and Hydrology Issues," (1999).[24] This study, requested by the French government to help resolve a contentious international issue, involved collaboration between an international team of hydrologists, geophysicists and geoengineers.

The Earth's unique 'container capability' is now being applied to a variety of waste disposal applications, including $CO_2$ sequestration, injection of drilling wastewater and probably others. Extraction of heat in EGS (Engineered Geothermal Systems) or minerals in 'borehole mining' also involve injection of fluids under pressure into rock at depth, from boreholes. All of these technologies introduce the potential of activation of slip on faults and fractures and the possibility of induced seismicity. All require a better understanding of the mechanics of these processes.

It is time now to recognize:

(i) The increasing scale of rock engineering problems;
(ii) Most rock engineering takes place within a tectonically loaded environment; and
(iii) Considerable mutual benefit can result from closer interaction between geoscientists and engineers.

This observation should not detract from the fact that there are also urgent applied rock mechanics problems that need to be addressed primarily by the respective engineering disciplines. Even here, interdisciplinary collaboration can result in valuable insights.

The complexity of the subsurface and its significance to the health of society invites comparison with that of the human body. However, while everyone is aware of the value of medicine and medical research, few in society have any notion of the vital role of the subsurface and subsurface technology -- except in the negative sense that extraction of (essential) mineral and fuel resources damages the surface environment. This situation needs to change.

### *Current Technological Issues in Rock Mechanics*

In discussing the application of mechanics to rock, it is important at the outset to reflect on the material with which we are dealing.

#### *Rock*

Although used frequently to evoke an image of permanence and stability, the term rock embraces a wide variety of materials and mechanical behaviors, and as it occurs *in situ*, it is arguably the most complex of engineering materials.[25] Rock includes hard, almost impermeable crystalline materials such as granites, quartzites, marbles; sedimentary porous and permeable sandstones and limestones; less permeable shales; ductile salts resulting from evaporation of ancient seas and oceans; and others. These materials have a wide range of constitutive behaviors. It also is not uncommon for different materials to be in close proximity to each other geologically.

Subject to successive epochs of tectonic and gravitational forces over hundreds of millions and as much as a few billions of years, these heterogeneous assemblies have been deformed and fractured, introducing a variety of planar discontinuities at various times and orientations in space, on a huge range of scales from microscopic grains to tectonic plates. The forces imposed on the rock are transmitted in part through the solid structure and in part also by the fluid in the pore spaces within the rock.

Slip on a discontinuity within the rock occurs when the effective shear stress ($\tau$) acting along the discontinuity reaches or exceeds the frictional resistance $\mu$ ($\sigma$ $-p$) along the fault, as indicated by the equation $\tau \geq \mu\ (\sigma - p)$, where $\sigma$ is the shear stress generated along the discontinuity by the tectonic and gravitational forces; $\mu$ is the coefficient of friction along the discontinuity and $p$ is the fluid pressure acting along the fault. It is seen that as $p$ increases, so does the propensity for slip, and vice versa. This relationship is of critical importance in a variety of rock engineering applications. All fluid injection/extraction technologies involve changes in fluid pressure.

We will now consider some specific examples of the complex nature of rock as an engineering material.

#### *Rock Mass Discontinuities and Anisotropy*

In his opening address at the first ISRM Congress in Lisbon, September 1966, President Leopold Müller identified two important features of a rock mass with respect to engineering problems as follows,

"...discontinuities and anisotropy are the most characteristic properties of a rock mass, and these properties depend much more on the properties of the interfaces between the rock blocks than on the rock itself."[26]

The technological importance of these features, he argued, was such as to justify the establishment of the International Society for Rock Mechanics (ISRM), the step he had taken in Salzburg (Austria) in May 1962.

Recent papers by Cundall and co-workers[27] describe how numerical models that include consideration of anisotropy introduced by large-scale discontinuities are now developing as practical tools.

#### *Rock Mass Heterogeneity*

Although not mentioned by Professor Müller, heterogeneity is an important feature of rock *in situ*, especially as the scale of problems increases. This is illustrated in Figures 1, 2 and 3.

Figure 1 shows the results of a series of in-situ stress determinations made at the Underground Research Laboratory at Bure, France, in sedimentary rocks of the Jurassic age (150-200 million years BP).

- continued -

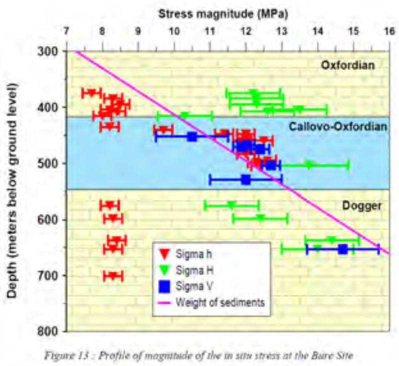
[24] Fairhurst C. et al. (1999) *Underground Nuclear Testing in French Polynesia: Stability and Hydrology Issues*, (1999), C.; http://conservancy.umn.edu/handle/11299/162862

[25] Although less complex than the human body.

[26] Numerical techniques to consider the role of discontinuities are now well developed, although three-dimensional anisotropic behavior is given less attention –due mainly to the computational demands of 3D analyses.

[27] (a) Cundall, P. A. "An Approach to Rock Mass Modelling," (2008) in *From Rock Mass to Rock Model — CD Workshop Presentations (15 September 2008) — SHIRMS 2008 (Proc. 1st Southern Hemisphere Int'l Rock Mech. Symp. Perth, Western Australia, Sept. 2008)*. Y. Potvin et al., Eds. Nedlands, Western Australia: Australian Centre for Geomechanics.
(b) Cundall, P. A., M. E. Pierce and D. Mas Ivars.(2008) "Quantifying the Size Effect of Rock Mass Strength," in *SHIRMS 2008 (op.cit.)*, Vol. 2, pp. 3-15.

It is seen that the stresses in the Callovo-Oxfordian argillite[28] are essentially isotropic (i.e., $\sigma_1 = \sigma_2 = \sigma_3 = \sigma_V = \rho g H$, where H= depth in meters and $\rho g \approx 0.25$ MPa/m; $\sigma_V$ is indicated by the blue straight line in Figure 1.), while in the overlying limestone, the overburden stress is the intermediate principal stress, and in the underlying limestone, the overburden stress is the maximum (i.e., most compressive) principal stress.




*Limestone* $\sigma_H > \sigma_V > \sigma_h$

*Argillite (Indurated Clay)* $\sigma_H = \sigma_V = \sigma_h$

*Limestone* $\sigma_V > \sigma_H > \sigma_h$

*Figure 1. In-situ stresses change with rock type (Underground Research Laboratory, Bure, France).*

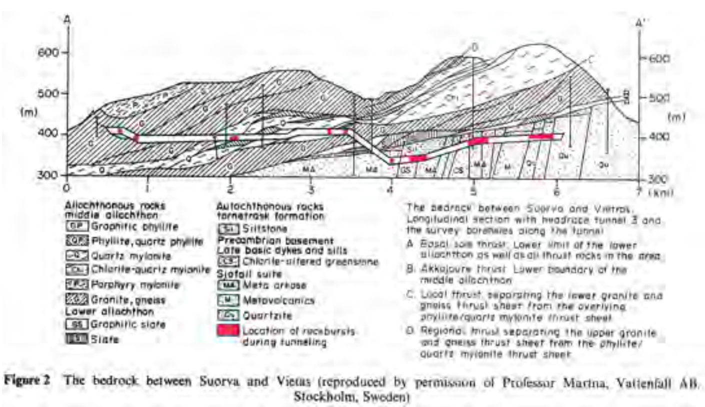



*Figure 2. High-stress variation encountered in a tunnel in Northern Sweden.*

Figure 2 shows an example of high-stress variations encountered while driving a tunnel in northern Sweden in crystalline rock formations. Rockbursts occurred at a number of locations (shown in red in Fig.2) during excavation. Measurements at these locations indicated in-situ stresses, "up to 10 times the calculated overburden stress,"[29] ($\sigma_x = \rho g H$, where H is the depth at the rockburst location). As seen from the two-dimensional section in Figure 2, the tunnel is located within a geologically heterogeneous site. The weight of the overburden may be carried primarily through a three-dimensional 'skeletal' structure with softer, more compliant formations being only lightly loaded.

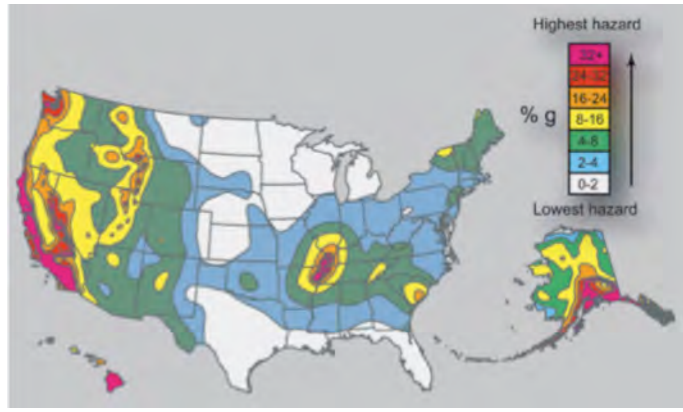
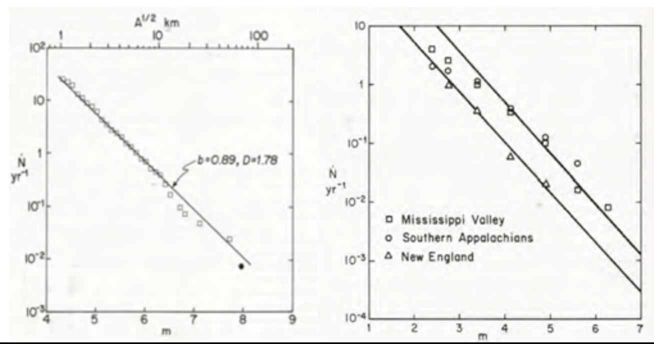



*Figure 3. Seismic Hazard Map of United States. (USGS 2010)*




In Southern California (above, left graph), the predicted frequency of a M5 earthquake approaches 10 per year.

In the Eastern US (above, right graph), the predicted frequency of a M5 earthquake varies between 1 in 10 years to 1 in 100 years, depending on the location.

*Figure 3(a) Two to three orders of magnitude lower probability of earthquakes in Eastern US compared to Southern California.*

*[ Gutenberg-Richter Earthquake Magnitude –Frequency Scaling; log (dN /dt) = - bM + log (da/dt) where a and b are constants].*

Figure 3 illustrates the heterogeneous nature of a rock mass on a Continental scale in terms of the probability of an earthquake of a particular severity across the continental United States. It is evident that this varies by many orders of magnitude across the continent. On a still larger scale, that of the interacting network of tectonic plates comprising the lithosphere, Gordon (2000)[30] has presented what he acknowledges to be a much over-simplified analysis to estimate strain rates of the various interacting plates and plate boundaries that comprise the lithosphere Each plate and boundary region is represented as a simple two-component Kelvin rheological model (Fig. 4), with an upper elastic region and lower viscosity region, and a single vertically averaged value for elasticity and viscosity. The appropriate parameters in this model span eight orders of magnitude in elastic strain rate and ten orders of magnitude in viscosity, viz:

- continued -

[28] This formation occurs also in southern England, where it is known as the Oxford Clay.

[29] Personal communication between Professor Martna and C. Fairhurst.

[30] Gordon, R.G., (2000) Diffuse oceanic plate boundaries : Strain rates, vertically averaged rheology, and comparisons with narrow plate boundaries and stable plate interiors, in *History and Dynamics of Global Plate Motions*, edited by M. Richards, R.G. Gordon, and R.D.van der Hilst, pp. 143-159, American Geophysical Union, Washington, D.C., 2000

## "Mechanics and Rock" (continued)

Elastic Strain Rate - from $10^{-12}$ /yr (Stable Plate Interiors & Diffuse Oceanic Plate Boundaries)

to $10^{-5.5}$/yr ~ $10^{-3.5}$/yr (Narrow Plate Boundaries)

Effective Viscosity – from $10^{16.5}$ Pa.s (Ocaeanic Transform Faults) to $10^{27}$Pa.s Single Plate Interior

This a very heterogeneous distribution of rock properties and tectonic forces. In reality, the heterogeneity will be manifest also in the third dimension.

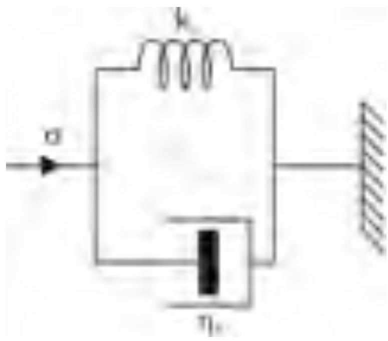


*Figure 4. Kelvin Rheological Model.*

The Kelvin model is depicted in Figure 4. In it: $\sigma = \dot{\varepsilon}(\eta_1 + k_1 t)$ where $t$ is the time that the constant strain rate, $\dot{\varepsilon}$, has been active, $k_1$ is the stiffness, and $\eta_1$ is the viscosity.

These values correspond to a stress change of the order of 1MPa/million years or less[31] in stable plate regions, such as the Canadian Shield, and much more rapid stress build-up in other plate regions.

These three examples all illustrate the heterogeneous nature of rock *in situ*. As with discontinuities, heterogeneity is a prominent characteristic of rock on all spatial scales. This results in a corresponding heterogeneity in the stress distribution in a rock mass. The stress distribution in the rock at any time is the result of interaction between applied tectonic and gravitational stresses over that time and the long-term constitutive behavior of the different components of the rock mass, including the fluids in this mass.

***Critically Stressed Earth***

As discussed above, rock *in situ* is in equilibrium with the tectonic and gravitational forces acting upon it. Any engineering activities will perturb that equilibrium, provoking a much shorter-term constitutive response of the rock. In some cases, this can result in major and perhaps devastating results, e.g., triggering of large earthquakes (or on a smaller scale, rock bursts in mines). In such cases, the term, 'Critically Stressed Earth,'[32] is frequently applied.

In other situations, these perturbations produce short term, essentially stable responses that are easily managed by engineering measures e.g., appropriate design of a mine layout or tunnel support system.

It seems, therefore, that while the Earth is subject to stress everywhere and has evolved over time to a state of hydro-mechanical equilibrium, and to a potentially dangerous critical stress in some regions (e.g., tectonic plate boundaries and large intra-plate faults), it may be well removed from this critical condition in other locations.

Given the public concern, both in the US and internationally, over the increased use of fluid injection into the subsurface for a variety of engineering applications, and the likelihood that such fluid technologies will find increasing use, there is an urgent need for research to improve our understanding and application of these technologies.[33]

***Numerical Modeling in Rock Mechanics***

As in other branches of science and engineering, the advent of high-speed computing and numerical modeling provides a potentially powerful design tool in rock mechanics and rock engineering. Rigorous closed–form solutions can be extended to take into account engineering variations, etc., such as described above. Unlike most other branches of engineering, practical problems in rock are characterized by variability, uncertainty and lack of data. This has important implications for the way in which numerical modeling should be used in rock mechanics.

As noted by Starfield and Cundall (1988),[34]

"One cannot use models in rock mechanics in a conventional way.[35]... "There is a need to adopt a distinctive and appropriate methodology for rock mechanics.... Plan the modeling exercise in the same way as you would plan a laboratory experiment."

The reference to 'laboratory experiment' is particularly appropriate. It is not possible to conduct classical laboratory studies to assess the influence, for example, of large-scale discontinuities on the response of rock to applied loads. It is certainly not possible to conduct enough such experiments to establish statistically reliable results.

Numerical modeling presents a valuable alternative to laboratory testing. In conjunction with field observations and (a relatively few) carefully planned field experiments, numerical models can help the field engineer arrive at an informed judgment[36] as to an appropriate design. In effect, computer runs become 'numerical experiments' in which the effect of changing input variables and replication allows the critical factors in the design to be identified. A few illustrative examples of the use of numerical modeling in rock mechanics will be presented below, in the context of problems encountered in the various engineering disciplines that deal with rock.

- continued -

[31] Damjanac, B, and C. Fairhurst. (2010) "Evidence for a Long-Term Strength Threshold in Crystalline Rock," Rock Mech. & Rock Eng., doi 10.1007/s00603-010-0090-9 (2010)

[32] Zoback, M.L. and Zoback, M.D., "Lithosphere Stress and Deformation, in Earthquake Seismology - Treatise on Geophysics," Vol. 6, ed. A. Watts and G. Schubert, Elsevier Ltd., Amsterdam, 253-274.

[33] "While the general mechanisms that create induced seismic events are well understood we are currently unable to accurately predict the magnitude or occurrence of such events due to the lack of comprehensive data on complex natural rock systems and the lack of validated predictive models." *Induced Seismicity Potential in Energy Technologies* (2013); Nat'l Res. Council. Executive Summary p 2 http://www.nap.edu/openbook.php?record_id=13355&page=2

[34] Starfield, A. M., and P. A. Cundall. (1988) "Towards a Methodology for Rock Mechanics Modelling," Int. J. Rock Mech., Min. Sci. & Geomech. Abstr., *25*(3), 99-106]. This short paper is recommended reading for anyone using numerical models in rock engineering.

[35] The "Conventional Way" refers to the use of models to arrive at precise designs, as followed in other branches of engineering where required input data is well defined and available.

[36] "The most powerful computer in the world isn't nearly as intuitive as the one we're born with." [1] President Obama - Brain Initiative Remarks, April 02, 2013 http://www.whitehouse.gov/the-press-office/2013/04/02/remarks-president-brain-initiative-and-american-innovation

## "Mechanics and Rock" (continued)

***Advantages of Mining and Civil Engineering - Observational Method.***

Mining and civil engineers have at least two important advantages over colleagues involved in other aspects of subsurface engineering:

- Direct three-dimensional access to the underground rock mass; and
- Practical experience extending over millennia.

Direct access to the subsurface allows direct observation and mapping of fractures and discontinuities in three dimensions (e.g., along exposures in the walls of underground excavations in different spatial orientations). These systems then can be represented as Discrete Fracture Networks (DFNs). DFN's are an essential component of the Synthetic Rock Mass. (SRM)[37] used to define the deformational and strength characteristics of a rock mass.[38]

Such developments notwithstanding, engineers are well aware that important uncertainties in characterizing the rock mass remain, and the actual behavior of the rock cannot be established reliably on the basis of design calculations alone. This has led to the so-called Observational Method,[39] or 'design as you go' approach in which an initial design is proposed based on estimated rock mass properties, incorporating features that allow design changes to be made on-site to correct any observed untoward departures from the expected behavior. The New Austrian Tunneling Method (NATM)[40] is a good example of this approach. Shotcrete[41] application equipment and rock bolts are available onsite in order to modify the initial design if instrument observations reveal behavior that departs significantly from that anticipated/desired.[42]

This advantage of direct underground observation and associated on-site design modification is not available to engineers involved in 'borehole access only' technologies. Developments to overcome this lack are discussed below.

Lengthy experience of the complexity of the rock mass, much of it obtained well before the advent of powerful numerical computational procedures, has resulted in empirical rock classifications and design rules used by mining and civil engineers. Such rules can now be evaluated against numerical predictions and their validity assessed. This is especially valuable as newer design projects extend beyond the range of experience on which the empirical rules are based.

***In-Situ Stress Determination***

Figure 5 is a simple, two-dimensional illustration of the difficulty of determining regional in-situ stress magnitude and orientation by measurements at single point locations. Boundary stresses of 40MPa and 20MPa were imposed on a 2D model of an isotropically elastic block containing several local cohesionless fractures/faults (friction coefficient $\mu$ = 0.5 in this example). Slip on such faults (which may be hidden from the individual making the measurements) can change stress magnitudes and orientations locally. Again, the influence of the faults will extend to three dimensions.

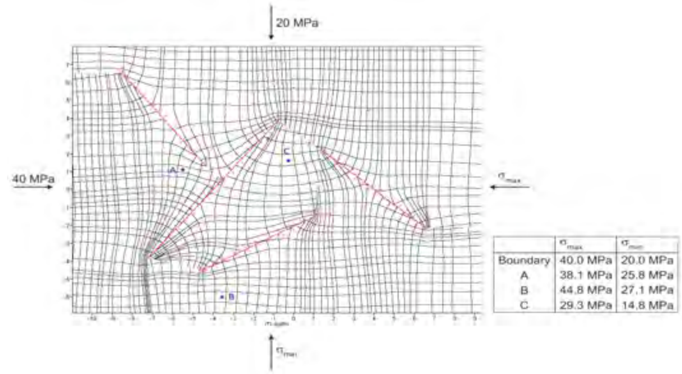



*Figure 5. Effect of fractures on in-situ stress magnitude and orientation.*

***Petroleum Engineering***

Commercial drilling for extraction of oil from a borehole started approximately 150 years ago, triggered by the Drake Well in Pennsylvania in 1859 http://en.wikipedia.org/wiki/Drake_Well.

There is a rich tradition of rock mechanics research in petroleum engineering. The early focus in engineering was on the challenging issues of drilling at depth, development of logging techniques to characterize the rock formations at depth; stability of deep boreholes and, from 1949[43] on, the study of issues associated with hydraulic fracturing to stimulate production in classical reservoirs, i.e., high-permeability oil bearing formations. Prediction of the direction and extent to which fractures would propagate was of particular concern; several approximate models, based on classical elastic theory, were developed as practical guides.[44]

The fact that the fractures are generated and extended by a pressurized fluid and that some of the fluid will leak off into the permeable formation presents significant analytical challenges.[45] It is assumed that once initiated at the borehole, the hydraulic fracture will propagate symmetrically from the well (Figure 6)[46].

The analysis is complicated by the fact that flow of the pressurized fluid flowing in the extending fracture is governed by the laws of fluid flow (Reynolds;Poiseuille) while fracturing of the rock at the crack tip is governed by Linear Elastic Fracture Mechanics (LEFM). In permeable rock, fluid 'leak-off 'into the rock further complicates the mechanics of crack propagation.

**- continued -**

[37] Footnotes 27(a) and 27(b) in this discussion provide details of the use of the SRM in numerical computation of rock mass deformation and failure behavior.

[38] The First International Conference on Discrete Fracture Network Engineering was held in Vancouver, Canada, Oct 19-22, 2014 See http://www.dfne2014.ca/

[39] http wikipedia.org/wiki/Observational method_(geotechnics)://en.

[40] See Schubert .W. (2008) "The Development of the Observational Method," *Geomechanics and Tunnelling*, *1*(5), 352–357, October. 2008

[41] See http://en.wikipedia.org/wiki/Shotcrete

[42] See also Fairhurst, C., and C. Carranza-Torres. "Closing the Circle — Some Comments on Design Procedures for Tunnel Supports in Rock," in *Proceedings of the University of Minnesota 50th Annual Geotechnical Conference (February 2002)*, pp. 21-84. J. F. Labuz and J. G. Bentler, Eds. Minneapolis: University of Minnesota, 2002.This paper can be downloaded directly from http://www.itascainternational.com/about/the-fairhurst-files.

[43] Standard Oil successfully patented and introduced the procedure to the US oil industry in 1949, but the idea of using fluid to fracture rock was well known earlier. http://www.iandiorio.com/pdf/PatentWatchDec.pdf

[44] http://petrowiki.org/Fracture_propagation_models

[45] D. Garagash, E. Detournay, and J. Adachi (2011), "Multiscale Tip Asymptotics in Hydraulic Fracture with Leak-off," *J. Fluid Mechanics,* 669, 260-297. doi:10.1017/S002211201000501X

[46] Figure 6, provided courtesy of Prof. Emmanuel Detournay, shows a fracture propagating normal to the axis of the borehole.

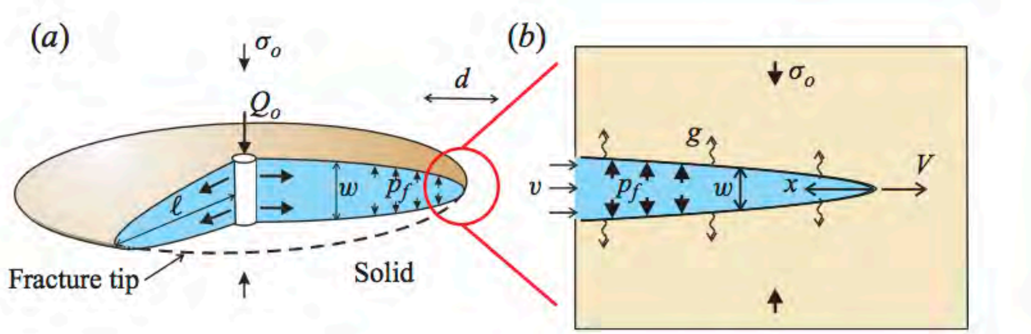
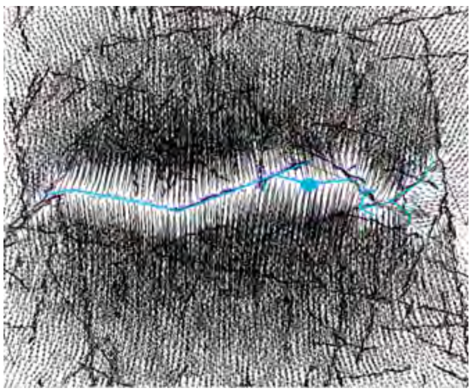



*Figure 6. Analytical model of a hydraulic fracture in an isotropic porous-permeable medium*

Such closed-form analyses provide powerful general insights into the mechanics of fluid-driven fractures in rock. The solution is expressed in terms of dimensionless groups, which allows the effects of scale of the problem to be assessed quickly.[47] The solution can also be used as a check on the validity of numerical extensions of the hydraulic fracturing problem. Numerical experiments, in which numerical analyses are used to examine the possible significance of practical features[48] not usually considered in continuum analyses, can provide valuable insights when standard laboratory experiments are not feasible, as in much of rock engineering.



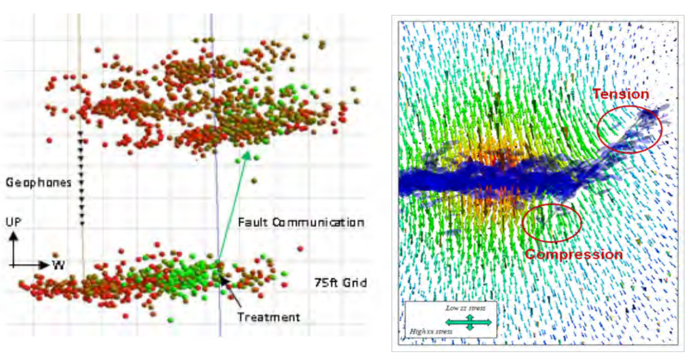
***Left: Figure 7. Two-dimensional numerical simulation of a hydraulic fracture in jointed rock.[49]***

Figure 7 shows a two-dimensional *PFC* [Particle Flow Code, (Itasca)] model of a rock mass containing a Discrete Fracture Network. The blue circle represents the borehole into which fluid is injected to simulate initiation and propagation of a hydraulic fracture. After an initial period during which the fracture propagates more or less symmetrically from the well bore, the fracture propagating on the right encounters pre-existing fractures. The fracture network on the right is oriented so as to act essentially as a greater barrier to propagation relative to the fractures on the left of the well bore. The result is a considerable asymmetry compared to the classical assumption of symmetrical propagation.

Note that the numerical example of Figure 7 does not 'invalidate' the results from the analysis of the model in Figure 6. Rather, it suggests, for example, that the jointed rock of Figure7 corresponds to some extent to that of Figure 6, but with different fracture toughness on each wing of the symmetrical crack.

Figure 8 shows the results of an actual hydraulic fracturing operation that was monitored microseismically from a downhole array of geophones in a well adjacent to the well to be fractured.

The green circles represent fracture locations detected at an early stage of the fracturing operation. Red circles represent fracturing late in the stimulation process. It is seen that the fracture starts at the intended fracture horizon, then 'jumps' to extend a fracture at a horizon some 120 m or so higher in the formation. Continued pressurization results in later fracture extension at both horizons.




(a) Left: Micro-seismic Indication of Upward Migration ( ~ 450ft) of Injected Fluid along Fault during Hydraulic Fracturing.

(b) Right: Numerical Explanation of 'Upward Only' Migration of Fracture.

***Figure 8. Microseismic record of evolution of hydraulic fracture.[50]***

**- continued -**

[47] *"The discovery of scaling laws very often allows an increase, sometimes even a drastic change, in the understanding of not only a single phenomenon but a wide branch of science. The history of science of the last two centuries knows many such examples."* Barenblatt, G.I. (2003). *Scaling*. Cambridge University Press, UK, 171p. Preface p.xiii

[48] This includes, for example, repeated 'runs' of the same model in which input parameters are varied systematically to examine the effects of data uncertainties on the output.

[49] Figure provided courtesy Dr. B. Damjanac, Itasca Consulting Group, Minneapolis. Note that the fractures in this two- dimensional model are assumed to be parallel to the axis of the borehole.

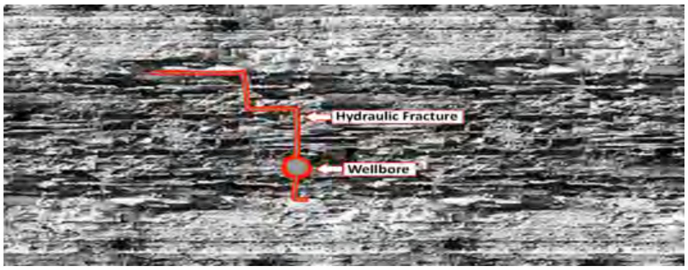
[50] Pettitt, W., J. Reyes-Montes, B. Hemmings, E. Hughes and R. P. Young. "Using Continuous Microseismic Records for Hydrofracture Diagnostics and Mechanics," in *SEG Houston 2009 (Proceedings, SEG International Exposition and 79th Annual Meeting, Houston, October 2009)*, pp. 1542-1546. Doi: 10.1190/1.3255143. Tulsa, Oklahoma: SEG.

## "Mechanics and Rock" (continued)

It was surmised that the initial fracture extension at the lower horizon encountered a pre-existing fault, creating a barrier to extension of the fracture at the original horizon, and allowing the fluid to flow up the fault until it reached a favorably oriented pathway.

Consider now the problem of hydraulic fracture propagation from a horizontal well in a 'tight shale' formation, as illustrated in Figure 9, which represents a vertical cross-section through a 'tight' (low permeability) shale.

*Figure 9. Hypothetical hydraulic fracture propagation path in a tight shale.[51]*




It is assumed that the minimum (least compressive) stress direction is horizontal, acting normal to the wellbore. The hydraulic fracture would then tend to propagate vertically from the borehole. Depending on the interfacial properties of the shale layers, the fracture may, as in the previous examples, propagate across a layer or be diverted along the layer, only to return to a vertical path later. Add to this a network of fractures (DFN) developed by tectonic loading subsequent to the original shale deposition process, and it is seen that the path of hydraulic fracturing can be far different from that usually assumed. Some reorientation of the stress field in the vicinity of the fractures generated will occur. What is the optimum location of the next well for further effective stimulation? It should be noted also that the percentage recovery of the in-place resource is quite low.[52] This suggests to the author that in-situ tests in shale seams conducted in underground coal mines could provide valuable insights into the mechanics of fracture propagation in shales, as a supplement to numerical modeling studies.

These examples illustrate the importance of a knowledge of the pre-existing fracture network. As noted earlier, this poses a significant problem in hydraulic fracturing and indeed, all borehole-based engineering problems, which do not have the benefit of direct access to the underground. Fractures can be accessed usually along the wall of the wellbore only. Determination of the DFN in these situations will require development of special geophysical or other technique.[53]

### *Observations on the State of Rock Mechanics/Mine Engineering in the U.S.*

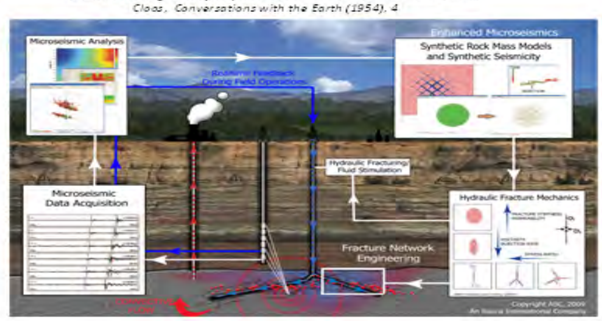
#### *The Observational Method via Boreholes*

The recent development of precise directional drilling by the petroleum industry, combined with hydraulic fracturing, has been so successful over the last decade that it promises to allow the U.S. to become fossil energy self-sufficient, and even an exporter of oil and gas within the near future. This has major economic and global political implications for US and other nations. The perceived drawback is that with continued dependence on hydrocarbon fuels, they contribute to global warming when burned[54].

The developments in numerical modeling and the value of on-site measurement and observation to monitor and modify the initial design, as needed, have led to the proposal[55] to extend the observational method to practical situations where direct 3D (i.e., human) access is not available.

This is illustrated in Figure 10 for the case of fluid stimulation of an underground site in rock. An initial numerical analysis is made to assess how the rock mass will react to the stimulation, and the associated microseismic response that would be expected at a downhole geophone array. If, as is very likely, the response differs significantly from that anticipated, the injection treatment is then commanded electronically to change such that the fracture development changes to conform more to that intended in the original design. Such a procedure will require considerable research and field development. Given the remarkable advances in control technology, e.g., those associated with directional drilling in petroleum engineering, and in other branches of engineering (e.g., space exploration technology), Fracture Network Engineering is not as fanciful a concept as it would have appeared to be a decade or so ago.

*Stones have begun to speak, because an ear is there to hear them. .....*
*Cloos, Conversations with the Earth (1954). 4*




**Fracture Network Engineering. - "21st Century Observational Approach"**
*Synthetic Rock Mass and Synthetic Seismicity Models are compared with observed microseismic signals for real time control of fracture network development. (Enhanced Geothermal Systems.)*

*Figure 10. Fracture Network Engineering.*

#### *The Broadening Role of Rock Mechanics*

Although the primary interest in many of these applications has been focused traditionally on the generation (and propping open) of fractures, it is now clear that more attention is needed on how the fluid penetrates into the rock beyond the fractures. It seems clear that fluid under pressure has produced slip on faults outside the region of engineering interest, and unanticipated seismic events at the surface. At the geothermal energy site in Basel, Switzerland in 2009,[56] earthquakes occurred up to two months after pumps were shut down and injection of fluids ceased. This is a clear indication of the need for a better understanding of how fluid flows into the formation in such

- continued -

[51] "Tight gas is held in pores up to 20,000 times narrower than a human hair" http://www.shell.us/aboutshell/shell-businesses/onshore/shale-tight.html.

[52] http://www.fool.com/investing/general/2014/05/05/the-bakken-shale-hits-a-billion-how-much-more-is-l.aspx

[53] Progress is being made. See D. Grae, G. A. Ugueto C., J. A. Roberts, H. Yamamoto, T. Oliver and G.Martine; *"Borehole Acoustic Reflection Survey (BARS) from Modern, Dipole Acoustic Logs for High-Resolution Seismic-Based Fracture Illumination and Imaging"* SPWLA (Soc. Petrophysicists and Well Logging Analysts), 53rd Annual Logging Symposium, June 16-20, 2012 Cartagena , Columbia .

[54] Zoback, Mark D and Douglas G, Arent (2014); *Shale Gas Development and Opportunities* https://www.nae.edu/Publications/Bridge/110801/111035.aspx?PopupId=36; and http://en.wikipedia.org/wiki/Shale_gas

[55] http://www.itasca-image.com/

## "Mechanics and Rock" (continued)

stimulation activities, and the geological characteristics of the site, e.g., this is a location that contains fracture systems and faults that may be brought to a critically stressed condition by the proposed engineering activity. This implies a close interaction between geologists familiar with the structural geological setting and engineers responsible for the injection program.

A recent report by the US National Research Council[57] indicates that the factor that appears to have the most direct consequence is the net fluid balance (total balance of fluid introduced into or removed from the subsurface), although additional factors may have an influence.

> "Projects with large net volumes of injected or extracted fluids over long periods of time such as long-term wastewater disposal wells and CCS would appear to have a higher potential for larger induced events. The magnitude and intensity of possible induced events would be dependent upon the physical conditions in the subsurface — the state of stress in the rocks, presence of existing faults, fault properties, and pore pressure. The relationship between induced seismicity and projects with large-volume, long-term injection, such as in large-scale CCS projects, is untested because no large-scale projects are yet in existence."

> "...due to expanding energy development, government agencies and research institutions may not have sufficient resources to address unexpected events. Forward-looking interagency cooperation to address potential induced seismicity is warranted."

The concern over the potential of CCS, and wastewater injection, to trigger significant seismic events if located inappropriately (i.e., in regions that may considered to be close to being critically stressed) suggests again the need for a close collaboration between geologists and engineers in the search for suitable disposal sites. As noted in the NRC report,

> "Methodologies can be developed for quantitative, probabilistic hazard assessments of induced seismicity risk. Such assessments should be undertaken before operations begin in areas with a known history of felt seismicity and updated in response to observed, potentially induced seismicity."[58]

***Three-Dimensional Cities/Complexity of Subsurface***

The tendency of populations to migrate to urban areas is clearly evident, especially in developing countries with large and growing populations. It is anticipated that over 80% of the world's 10+ billion people will be living in cities by 2100.[59]

Vigorous efforts are being made in existing cities to accommodate this increase (e.g., Asia), but development of the subsurface in such cases can encounter severe difficulties. Many existing cities have developed over centuries without little or no planned use of the subsurface. Supply of drinking water, installation of wastewater disposal systems, gas and electrical supply lines, etc., were simply placed wherever space could be found underground. In some older cities, e.g., in Europe, there are no records of where various facilities have been placed. Figure 11 shows the situation revealed in Wall Street, New York City, ca. 1917 when the street was excavated. Such situations can increase costs where change is required, either to existing systems or to the installation of new facilities.

As noted in a recent report on the current rate of urbanization internationally, "1.4 million people are being added to urban areas each week, roughly the population of Stockholm."[60]

Given this pace of urbanization, one that will continue to accelerate over the coming decades of the 21st Century, it seems wise to consider including the third dimension, i.e., the subsurface, as part of the city design. In some regions, where cities do not exist currently, development of 'three-dimensional cities' should be the preferred option in many locations.

*Figure 11. Subsurface facilities revealed during excavation, Wall Street, New York (ca. 1917).[61]*

In 2004, Japan created a public zone for deep underground space beneath major cities to ease the administrative burden of developing major underground infrastructure linkages.[62]

Some four decades ago, the renowned city planner C.A. Doxiadis,[63] is reported to have commented, "We ought to learn from biology and go underground. In biology, the circulation systems are always on the inside. Eventually, all urban transit will have to go underground, no matter what the cost." Doxiadis (1974)[64]

In fact, in 'biology' most critical 'life-support systems' are 'on the inside' — cushioned from damage due to surface insults to the system. There is considerable truth in this observation.

Further testimony to the growing recognition of the importance of the subsurface in addressing urban problems, is provided on the following two websites, both of which appeared within the past two weeks or so www.cnn.com/2014/11/18/business/underground-cities/ and www.youtube.com/watch?v=jXNyEiw28D0. This is a BBC commentary on the use of the subsurface in city planning.

- continued -

56 http://en.wikipedia.org/wiki/Induced_seismicity_in_Basel
57 *Induced Seismicity Potential in Energy Technologies* (2013) US Nat. Res. Council. see http://www.nap.edu/catalog.php?version=b&utm_expid=4418042-5.krRTDpXJQISoXLpdo-1Ynw.1&record_id=13355&utm_referrer=https%3A%2F%2Fwww.google.com%2F
58 http://www.nap.edu/openbook.php?record_id=13355&page=R5
59 http://ensia.com/infographics/the-global-population-in-2100/ See also http://en.wikipedia.org/wiki/Urbanization
60 http://newclimateeconomy.report/cities/
61 *Underground Engineering for Sustainable Urban Development*.(2013) National Research Council Report (2013) http://www.nap.edu/catalog/14670/underground-engineering-for-sustainable-urban-development (See Box 1.5 p.30 Sustainability of Underground Utility Design )
62 Dr.R.A. Sterling, Personal communication
63 http://en.wikipedia.org/wiki/Constantinos_Apostolou_Doxiadis
64 C.A. Doxiadis quotation in Readers Digest, Jan.1974 p.30.

*Figure 12. Three-dimensional city concept.*

***Use of underground space to create new commercial space linked to transportation and utility infrastructures while freeing up precious surface space. (Illustration - Dr. Tetsuya Hanamura, Taisei Corporation, Japan) See also (i) similar concept in NRC Report, Underground Engineering for Sustainable Urban Development (Footnote 44) p.59. (ii) ‘Multi-disciplinary Research aiding Domestic Competitiveness’ - Box 7.3, p.195).)***

### *Mining Engineering in the United States*

A position paper [65] published by the Society of Mining Engineers (SME) in March 2013 states,

> “As of 2012, in the United States, there are 12 degree programs in Mining Engineering. Over 50% of the faculty are likely to retire within the next five years. With low student enrolments and few Ph.D. faculty replacements available, several universities may decide to eliminate the degree program.”

Apparently, if the number of remaining programs falls below 10, ABET[66] will no longer accredit the discipline. Thus, Mining Engineering could disappear as an accredited engineering discipline in the US within a few years. Is this in the best interests of the US?

Today, nine of the 10 largest mining companies in the world are based outside the US,[67] although most companies operate mines here,

> “Loss of people in the mining industry means loss of domestic and global leadership and loss of national economic and defense security regarding minerals that are a basic necessity for quality of life.”

The comment by Agricola[68] made in 1556 is as true today as it has always been,

> “...none of the arts is older than agriculture, but that of metals [minerals] is no less ancient...for no mortal man ever tilled a field without implements. If we remove metals (minerals) from the service of man, all methods of protecting and sustaining health and more carefully preserving the course of life are done away with.”

This fact is hidden in the US today, since mining is a small part of the national economy. “In the U.S. currently, the ratio of the entire US manufacturing sector to the mining sector is about 52 to 1, whereas in Australia, a much less populous but similarly affluent country with a comparable mining industry, the ratio is 1 to 1”.[69] In Canada it is 4 to 1.

Even though less than 2%, of the U.S. manufacturing sector, minerals are, as always, the foundation of the economy.[70] If the foundation is missing, the entire superstructure will collapse.[71]

Closure of the US Bureau of Mines by the US Congress in 1995 eliminated an important source of mining R&D, both within the Bureau and through support of research at universities. Equipment suppliers to the mining industry do carry out substantial R&D, but this leaves significant gaps (e.g., ground control) in research activity. It has been stated that the last ‘revolution’ in underground mining technology took place after WWII when German mines introduced longwall coal-face mechanization, based on the armored conveyor (“Panzerförderer”).[72] No such revolution occurred in hard rock mining. An important concern in hard rock is improvement in productivity by ‘rapid excavation.’ The National Science Foundation’s RANN (Research Applied to National Needs)[73] initiative in the 1970’s included a program to develop faster rates of rock excavation, and to the establishment of the ***Rapid Excavation*** [emphasis added] and Tunneling Conference (RETC) in the early 1970’s. Although RETC is now a major international conference,[74] covering many advances in tunneling, rates of advance have not increased in the dramatic fashion originally anticipated. (See, for example, Nuclear Subterrene.[75])

**- continued -**

[65] https://www.smenet.org/docs/public/USMiningSchools-SME.pdf

[66] ABET - Accrediting Board for Engineering and Technology (See also http://en.wikipedia.org/wiki/ABET)

[67] Freeport McMoRan Copper & Gold, based in Phoenix, AZ is No.7 in the list of 10 companies http://www.mining-technology.com/features/featuremining-giants---the-top-ten-richest-mining-companies-4203262/

[68] Agricola’s series ‘De Re Metallica’ are considered to be the world’s first textbooks in Mining, used for almost 200 years. Translated into English in 1912 by Herbert Hoover (US President, 1929-1933) and his wife Lou Henry Hoover. See http://en.wikipedia.org/wiki/De_re_metallica and http://www.gutenberg.org/files/38015/38015-h/38015-h.htm Metal’ and ‘mineral’ were considered synonymous in the time of Agricola.

[69] Freeman L.W. and R.P Highsmith (2014) Supplying Society with Natural Resources THE BRIDGE, US Nat’l Acad. Eng https://www.nae.edu/Publications/Bridge/110801/111052.aspx

[70] In 2013, the US was totally dependent on imports for 19 minerals and over 50% dependent on imports for 22 more. In 2013, the supply for more than one-half of U.S. apparent consumption of the 40 mineral commodities shown in the figure [table on p.6] came from imports, http://minerals.usgs.gov/minerals/pubs/mcs/2014/mcs2014.pdf (See p.6)

[71] This became clear during the brief Rare Earth’s ‘scare’ of 2010 see http://www.smh.com.au/federal-olitics/political-opinion/scare-over-rareearth-minerals-underlines-fear-of-a-rising-china-20100927-15u0j.htm

[72] Lack of availability of natural rubber led German engineers to develop steel flight conveyors running in robust guides. These guides served as rails, allowing the coal plough (and, later, coal shearers) to traverse the coal face, discharging the coal directly onto the flighted conveyor. Since Germany lost all patent rights at the end of WWII, companies in Allied countries moved quickly to develop similar technology. The fully mechanized faces seen almost universally in coal mines today are a direct development of the German innovation. This change resulted in major increase in coal mine productivity.

[73] http://www.nsf.gov/about/history/nsf50/nsf8816.jsp See Chapter IV Tumultuous Times 1968-197

[74] See also https://www.ita-aites.org/en/.

[75] http://www.osti.gov/scitech/servlets/purl/7111588

## "Mechanics and Rock" (continued)

Mining Engineering programs at U.S. universities have suffered compared to other engineering disciplines from the lack of vigorous Ph.D. programs. The relative lack of funding mentioned above was compounded by a lack of industry R&D, and little opportunity within the industry for doctoral graduates to be employed directly in mining. Leading U.S. universities are judged on the strength of their Ph.D. programs. This places Mining Engineering at a disadvantage with respect to other engineering disciplines. This is starting to change with (i) mergers and the emergence of large corporations, and an increased awareness on the part of companies of the need for improved technology (e.g., rapid excavation); (ii) the interdisciplinary nature of engineering research problems; Ph.D. students from many disciplines can work in teams to solve problems in mining, without necessarily feeling limited to research opportunities in that subject or industry upon graduation. Development of Interdisciplinary Centers of Excellence for study of challenging mining research problems is a logical way to stimulate research and technical progress in the industry.

***Underground Research Sites and Laboratories/New Opportunities.***

The existence of large-scale geological features such as joint and fracture systems that can have a dominant influence on rock mass behavior, and the fact that these critical factors cannot be duplicated in the classical laboratory setting, has been stressed throughout these notes. "The Field is the Laboratory!"

The international[76] search for permanent underground repositories for high-level nuclear waste has been ongoing since the late 1950s. In all cases, it is recognized that even after very diligent geological assessment, final determination of the suitability of a proposed site must involve field-scale experiments underground.

Underground Research Laboratories have been established around the world (some examples are listed below). The existence of sites in a variety of geological settings provides an opportunity to test the applicability of a concept, instrument, etc., in different environments.

- Aspo (Sweden) Granite; www.skb.se/upload/publications/pdf/Aspo_Laboratory.pdf
- Mol (Belgium) Clay; publications.sckcen.be/dspace/handle/10038/8201
- Bure (France) Clay; www.andra.fr/download/andra-international-en/document/editions/182.pdf
- Mont Terri — Sedimentary; www.mont-terri.ch/internet/mont-terri/en/homepage.html
- Grimsel — Granite (Switzerland); http://www.grimsel.com/
- Horonobe — Sediments (Japan); www.jaea.go.jp/english/04/horonobe/
- Mizunami — Crystalline rock (Japan) esd.lbl.gov/research/programs/new/research_areas/international/japan.html

Most of these laboratories are receptive to international co-operation, and willing to discuss requests for specific experiments. Other opportunities may be present by collaboration with operations in mining and civil engineering.[77] As mentioned earlier in these notes, it would seem, for example, that considerable insight into fracture development and gas production in tight shales could be gained from tests in low permeability shales accessible in underground coal mines.

The important attribute of field studies in deep mines to contribute to earthquake research has also been recognized by McGarr.[78] More recently, researchers at the University of Oklahoma[79] have also identified a particular attribute of studies in active mines — the ability to observe slip processes close to their source.

"The physics of earthquake processes has remained enigmatic in spite of major advances during the last few decades. One major obstacle in earthquake investigations is the lack of direct and near-field observations that are essential for the validation of models and concepts. We propose to significantly reduce this limitation by investigating seismogenic processes at focal-depths of earthquakes in deep gold mines of South Africa."

The US Department of Energy's Office of Geothermal Systems also has announced plans to develop its own underground site, under the Frontier Observatory for Research in Geothermal Energy (FORGE) project.[80] A budget of $31 million is designated for initial studies. Underground sites for study of Engineered Geothermal Systems (EGS) exist in Europe and other countries.

***Earth Resources Engineering in the US — The Future?***

The graph of World Population, shown as Figure 1 in Part I of these notes indicated how rapidly this population increase has increased over the past 200+ years. It is interesting to observe how the application of mechanics in engineering has changed over this period. Mechanics was a topic for scholarly discussions from the time of Aristotle and Greek philosophers of the 4th century B.C. to the middle of the 19th century.[81] Although Newton's *Principia* and his *Laws of Motion* appeared in 1687, his work had little influence on either the start or development of the Industrial Revolution in England some 70 or more years later. Empiricism guided development of the steam engine, locomotives, etc., and the first airplane and flight by the Wright brothers in 1903. This had changed dramatically by the end of WWII in 1945 when development of supersonic rockets was the result of close interaction between applied mechanics and experiment. Today's developments in space exploration, global communication, high-speed computation all depend on intimate theory-practice linkage.

Application of mechanics in Earth Resources Engineering has lagged applications in other disciplines, with empiricism still a strong component of much of subsurface engineering. This is due in large part to the mechanical complexity of the subsurface, as illustrated earlier in this note.

**- continued -**

[76] http://esd.lbl.gov/files/research/programs/new/lbnl-59808-wwr4.pdf

[77] The Mont Terri Laboratory was developed as an 'add-on' tunnel from a highway transportation tunnel. Dr. Joe Wang at Lawrence Berkeley National Laboratory (jswang@lbl.gov) is promoting such collaboration and provides a useful initial contact

[78] A McGarr (1993) "Factors influencing the strong motion from mining –induced tremors," Keynote Address, Rockbursts and Seismicity in Mines, R. P. Young. ( Editor) Balkema, Rotterdam.

[79] NELSAM (Natural Earthquake Laboratory in South African Mines) See http://earthquakes.ou.edu/NELSAM_NSF_CD.pdf

[80] http://www.energy.gov/eere/forge/forge-home

[81] See Filonenko- Borodich (ca.1960) *Theory of Elasticity – Introduction*. English version, Foreign Languages Publishing House, Moscow, USSR.

## "Mechanics and Rock" (continued)

There have been some remarkable developments, as in the case of directional drilling and hydraulic fracture technology in petroleum engineering — the component of Earth Resources Engineering that has a strong tradition of industrial R&D laboratories. The truly remarkable effect of this technological development has resulted in major change of US (fossil) energy dependency with associated international economic and political consequences. The technology also has stimulated strong public concerns, both in the US and internationally, with respect to the environmental implications.

Much of the global population growth is occurring in developing regions, such as Africa. Development of natural resources is a primary concern in developing regions, as it has been throughout history. This implies a central role for Earth Resources Engineering. Who will provide state-of-the-art technological assistance to these countries?

It is important that the US, through its engineers, be centrally involved.

Mineral resources are distributed globally and, as noted earlier, the US economy is heavily dependent on imports for a large fraction of the minerals that underpin the nation's economy. Being a global leader in mineral resource technology is the most reliable way to secure a place at the table in discussions of global resource development, and hence, help assure a supply of minerals to the nation.

The problem currently facing Mining Engineering in the US has been mentioned earlier. This is compounded by the fact that some of the regions now emerging as competitors to the US (e.g., China, South America) are very vigorously involved in development of Earth Resources and associated engineering, and have more engineers involved, as is evident from the following comments.

Although referring to engineering in general, the situation applies very much to Earth Resources Engineering. According to a 2012 National Science Board report,

> "The percentage of undergraduate engineering degrees among all undergraduate degrees in the US was 4%, among the smallest national percentages in the world. For a sense of scale, the average percentage in key Asian countries (India, Japan, China, Taiwan, South Korea, and Singapore) is 23%, and in European countries (United Kingdom, Sweden, Finland, Denmark, Germany, and France) it's 13%. In short, the percentage of US engineering graduates among all its graduates is one-third of the European average and one-sixth of the Asian competitor average."

Countries in those regions are substantially increasing the competition for international talent. In 2007, the former President of China, Hu Jintao, stated,

> "The worldwide competition of overall national strength is actually a competition for talents, especially innovative talents."

According to Dan Mote, President of the U.S. National Academy of Engineering,

> "I read this as primarily 'engineering talents,' those who create value for humanity and society, (2013)"[82]

Add to this, the relative size of populations in each country, e.g., China 1.39 (billion); India 1.27 (billion); USA 0.32 (billion), and the magnitude of the challenge is clear.

President Mote re-emphasized the challenge in 2014,

> "Recruitment of talented international students over the past half century, mostly at the graduate level, has contributed remarkably to US engineering,[83] and has compensated for this deficiency in undergraduate degree numbers. The large number of first- and second- generation Americans that founded start-up companies reflects this understanding. However, times have changed. For one thing, virtually every society globally, friend and adversary alike, is recruiting engineering talent aggressively, and particularly the "in-demand" talent with current skills. Talent is the coin of the global engineering realm. Increasingly, attractive opportunities for engineers that offer excellent salaries, facilities, and economic growth potential are in Asia and the Middle East, and soon in Africa."[84]

This is indeed a Grand Challenge for Earth Resources Engineering in the U.S. The question, then, is "How should we address the Challenge?"

The National Laboratories are an excellent U.S. asset, and certainly have a role to play in meeting the Challenge but, as seen from the discussion above, a primary issue is to increase the supply of engineers for the future. This is the responsibility of universities. The following comments are directed towards this part of the Challenge.

- ***Interdisciplinary Centers of Excellence in Earth Resources Engineering***

Leading US universities have developed an excellent tradition of interdisciplinary research. It is time now to develop Interdisciplinary Centers of Excellence in various aspects of Earth Resources Engineering (ERE) at such US universities. Although not all of the centers would be centrally concerned with rock mechanics and rock engineering, mechanics is a major component of many challenges in ERE, and there is considerable potential for advance.

Fundamentally similar to classical fracture mechanics, rock fracture mechanics has the added complications of scale effects. Increasing scale of a problem introduces new sets of fractures, geological complexity and heterogeneity. As noted by Chorin,[85]

> "We are at the age of multi-scale computation, with a growing need to understand not only phenomena on each of many scales, but also the interaction between phenomena at very different scales."

Several interdisciplinary Centers have already been launched. More are needed. The *Global Climate and Energy Project* directed by Prof. Sally Benson at Stanford University, https://gcep.stanford.edu/ is a prominent example.

**- continued -**

[82] http://www.nae.edu/Projects/Events/AnnualMeetings/2013AnnualMeeting/89114.aspx

[83] See also testimony of former NAE President W. A. Wulf Sept 15,2005 ceg https://www.aau.edu/WorkArea/DownloadAsset.aspx?id=6458

[84] Eloquent tribute to the dependence of US Engineering on contributions of foreign–born scientists and engineers was also paid in 2005 by former NAE President William A. Wulf, in testimony before a Committee of the US House of Representatives. This is well worth reading.

[85] Alexandre Chorin, Univ. Professor, Univ. of California, Foreword to *Scaling*, by G.I. Barenblatt, Cambridge Univ. Press (2003)

## "Mechanics and Rock" (continued)

The team led by Professor Klaus Regenauer-Lieb.at CSIRO/University of Western Australia, Perth[86] is an example from Australia. This stimulating group has developed as a consequence of studies by CSIRO, and discussions such as those at the 19-24 August, 2001 Chapman Conference, Western Australia.[87] Another, with which the writer has been associated recently, is the Center for Engineered Fracturing of Rock at the University of Minnesota.[88] Others are needed.

- ***Federal Office for Earth Resources Engineering***

Public concern over potentially serious and lasting environmental damage due to Earth Resource Engineering (ERE) projects is understandable, given the legacy of environmental damage resulting from ERE and related projects in the past.[89] Even so, it is critically important that the public recognize that products from the subsurface (be they minerals, potable groundwater, fossil fuels, geothermal energy, etc.) applications of the 'container' role of the subsurface, are all essential life-support systems for society, and all involve engineering.

A publically funded Federal Office for Earth Research Engineering, established to conduct research to advance engineering in the public interest, should help to reduce tensions between the industry and the public. In some sense this office would be a 21st Century version the U.S. Bureau of Mines, but with a broader engineering mandate than that for the past century. This office could also oversee the development of the Centers of Excellence program at universities.

How much would this cost?

Centers of Excellence at the National Science Foundation are funded typically at around $5 million/yr for an initial five-year period, with the option to be extended for a second five-year period if warranted by performance over the initial five years.

When closed in 1995, "almost $100 million, or 66%, of its 1995 programs ceased"[90] Adjusted for inflation, $100 million in 1995 is equivalent to $156 million in 2014.

Thus, if we assume an initial group of 10 Centers of Excellence, each funded at $5 million/yr, and administered by the Federal Office, and a $150 million/yr Center, the initial budget for the program would be $200 million/yr.

How does this compare with other Federal programs that have some association with Earth Resources Engineering?

The US Geological Survey has an annual budget of the order of $1 billion/yr. A press release dated 4 March, 2104 announced,

> "President's 2015 budget proposes $1.1 Billion for the USGS in targeted investments to advance research on climate change and earth sciences to support community safety, health, and economic growth." [91]

Currently, the primary source of financial support for university research related to rock mechanics is the National Science Foundation. It is difficult to provide a precise amount for this support, because there is no specific rock mechanics program. NSF has several programs to which rock mechanics-related proposals can be directed.[92]

$2 million/yr seems to be a reasonable estimate of NSF funding for university research in rock mechanics. Clearly, if the US is to develop world-class competence in Earth Resource Engineering, and a sufficient workforce of engineers to provide the nation with a global presence, the first steps are (i) establish a Federal office that acts in the public interest to help develop and maintain a capability in Earth Resource Engineering;[93] and (ii) develop first-rate graduate programs at leading US universities. This will require funding, initially of the order of $200 million per year.

To put such a national investment into perspective, one only has to reflect on the multi-billions of dollars in cost of environmental damage caused by recent accidents.[94]

Absent an investment of this order, it will be difficult to follow François Cornet's admonition,

"Today geoengineers and geoscientists dealing with the mechanics of Earth materials must speak the same language." (p.2 of these notes) - since Earth Resource Engineers in the United States will be in very short supply!

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[86] Regenauer-Lieb, K., M. Veveakis, T. Poulet, F. Wellmann, A. Karrech, J. Liu, J. Hauser, C. Schrank, O. Gaede, and F. Fusseis (2013), Multiscale coupling and multiphysics approaches in earth sciences: *Journal of Coupled Systems and Multiscale Dynamics*,
Part 1 – Theory, Vol. 1(1)/2330-152X/2013/049/025
Part 2 - Applications, Vol 1(3)/ 2330-2152X/2013/2001/2042, doi:10.1166/jcsmd.2013.1021 J. Co. http://www.csiro.au/Organisation-Structure/Divisions/Earth-Science--Resource-Engineering/KlausRegenauer-Lieb.aspx

[87] http://www.earthbyte.org/Events/ChapmanConference/Overview.html (See power points - Introduction and Summary). The paper G. C. Hall and P. W. Holyland (2001), "The use of numerical modeling in exploration by Placer Dome Inc." at this conference, discusses the use of continental –scale modeling to identify potential zones of mineralization.

[88] www.cefor.umn.edu.

[89] http://en.wikipedia.org/wiki/Berkeley_Pit

[90] http://en.wikipedia.org/wiki/United_States_Bureau_of_Mines.

[91] http://www.usgs.gov/newsroom/article.asp?ID=3817#.VJAusdLF_HA.

[92] Some examples are: Major Research Instrumentation (MRI) for equipment (several awards in recent years for rock testing equipment); Partnerships in International Research and Education (PIRE); Hazard SEES (for landslide or seismic hazards); and Integrated NSF Support Promoting Interdisciplinary Research and Education (INSPIRE). The EAR [Earth Sciences Program] in GEO [Directorate for Geosciences] also funds some rock mechanics awards, but of course work more related to geosciences than engineering. Dr Richard Fragaszy, whose responsibilities include directing the Geotechnical Engineering and Materials (GEM) program kindly supplied this information (Dec 15,2014). He stated, "Last year, my combined programs funded approximately $7.5 million of awards, of which about $1.1million went to rock related research. This is approximately in proportion to the number of proposals in rock vs. soil."
http://www.nsf.gov/mobile/staff/staff_bio.jsp?lan=rfragasz&org=MPS&from_org=MPS

[93] We aspire to an engineering capability comparable to that of the USGS capability in Earth Sciences.

[94] http://en.wikipedia.org/wiki/Deepwater_Horizon_oil_spill