A REPORT TO THE NATIONAL SCIENCE FOUNDATION

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NEW DIRECTIONS IN ROCK MECHANICS - A FORUM SPONSORED BY THE AMERICAN ROCK MECHANICS ASSOCIATION

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Written By:

STEVEN D. GLASER

Professor, Dept. of Civil and Environmental Engineering

University of California, Berkeley, CA, 94720

DAVID N. DOOLIN

Graduate Research Assistant, Dept. of Civil and Environmental Engineering

University of California, Berkeley, CA, 94720

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Executive Summary

The American Rock Mechanics Association (ARMA) and the ARMA Foundation sponsored a forum on New Directions for U. S. Rock Mechanics, held at the Asilomar Conference Center in Pacific Grove, California, October 18-20, 1998. The goal of the Forum was to focus on 1) a strategic vision for the future of rock mechanics in the United States, 2) the identification and delineation of critical issues facing the rock mechanics community, 3) the role of research in addressing these issues, and 4) critical areas of research in each of the topic areas addressed at the forum including examples of specific research initiatives.

To a large degree, rock mechanics has been used successfully to model and predict the behavior of fractured rock masses for building large structures. However, improvements on present success, and future advances at modeling and construction, are predicated on better characterizing fractured rock masses. This will require increasing emphasis on non-linear and discontinuity-based models to reflect the mechanisms at work in fractured rock masses. For example, relevant characterization schemes, as well as field, laboratory, and logging techniques have yet to be developed for weak rock conditions and for all but the simplest fluid flow conditions.

This report summarizes two days of discussion held during the Forum. It was the sense of the Forum participants that fundamental improvements of *in situ* characterization is of the utmost importance. Every session emphasized that obtaining valid information from large volumes of rock is the prerequisite for the effective and improved practice of rock mechanics. Research and application of remote imaging and nondestructive evaluation of the subsurface should provide a source of economically realizible data from extremely large volumes of rock. This area should be a primary goal of future research.

Associated with the question of site characterization is the degree of uncertainty associated with the data, and with the chosen interpretive model itself. Forum participants also recommended conducting research to find implementations of stochastic techniques, which would allow uncertainty to be dealt with in a rational manner.

Authors' Note

This report represents our best attempt to report accurately and fairly what transpired at the 1998 Asilomar Forum. While every attempt was made to give each voice an equal place, the manuscript does contain many of the authors' opinions. Given that the Forum was designed for participants to state their opinions, we do not think stating ours is out of place.

The purpose of the Forum and of this manuscript is for the members of ARMA and the U.S. and international rock mechanics community to express viewpoints on where rock mechanics has been and where it is going. It was not and is not a thorough state-of-the-art review, such as the 1981 National Academy of Sciences report on rock mechanics research requirements[*].

We wish to thank all the participants, from the United States as well as Europe. Without their work before, during, and after the Forum, we would have nothing to report.

[*] National Research Council, (1981) *Rock Mechanics Research Requirements*, National Academy Press.

1. Introduction

1.1 The Forum

In a departure from the traditional format of annual U.S. rock mechanics symposia, which emphasize technical presentations, the 1998 Asilomar Forum was structured to encourage attendees to explore and exchange ideas on possible new opportunities and new directions for rock mechanics in the United States. The format of the meeting was similar to the Society of Petroleum Engineers' Forums or the American Geophysical Union's Chapman conferences.

The goal of the Forum was to provide the opportunity for participants to shape the future of rock mechanics in the U.S. through ARMA by discussing the following specific issues:

1. a strategic vision for the future of rock mechanics in the United States;
2. identification and delineation of critical issues facing the rock mechanics community;
3. the role of research in addressing these issues; and
4. identification of critical research areas in each of the topic areas addressed, including examples of specific research initiatives.

The Forum was organized into eight consecutive sessions on subjects important to the rock mechanics community. Each session was hosted by an invited expert who was asked to present 20 minutes of overview and background on the topic and serve as facilitator for that session, challenge current dogma, and be controversial. In addition to session hosts, each session had a technical panel, of which each member was appointed to speak for five to ten minutes. Panelists were chosen so that there was balance from the civil, mining, and petroleum engineering communities. All participants were encouraged to contribute to the discussion, which they did; sessions were lively and opinionated.

The Forum attracted 49 attendees, representing a wide variety of rock mechanics practitioners. The private sector was represented by 21 attendees, as was academia, with the government sector represented by 8 attendees. Professional interests were evenly divided among petroleum, mining, and civil applications, with another quarter expressing over-arching interests. A group photograph of the attendees is presented in Figure 1.

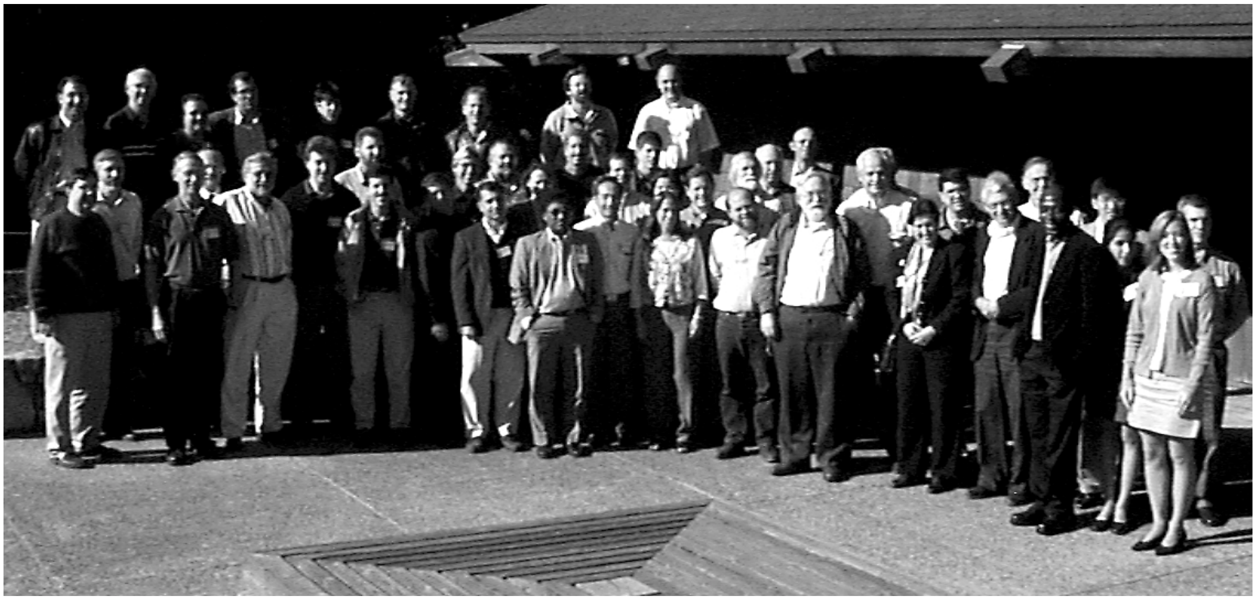

Figure 1. Attendees of the ARMA Forum, New Directions for U. S. Rock Mechanics, held at the Asilomar Conference Center in Pacific Grove, California, October 18-20, 1998

1.2 Background

The American Rock Mechanics Association, the first membership organization for U.S. rock mechanics, was formed in 1994 as an outgrowth of concern that U.S. rock mechanics needed revitalization with greater involvement of the professional community. Since 1994, ARMA has been developing a variety of means for serving the needs of the rock mechanics community. Beginning in 1999, ARMA assumed primary responsibility for the annual U.S. rock mechanics symposium.

Rock mechanics, as a distinct technical discipline in the United States began in the mid-1950's. Similar activities were underway in Europe, leading to the formation of the International Society for Rock Mechanics (ISRM) in 1962. The practitioners who participated in this early development are now completing their careers, and rock mechanics as an engineering and practical discipline is experiencing a significant turnover in leadership.

Contributing to the present climate of change in rock mechanics is the simultaneous reordering of the relationships among industry, academia, and government. Rock mechanics research is becoming increasingly constrained by reduced government support and short-term objectives by industry. Meanwhile, the private sector, notably mining and petroleum, has undergone severe restructuring, which has strongly altered the climate in industrial research. As a result, academic research is experiencing significant shifts away from grants for basic research towards government-industry cooperation and funding of research. The Forum was convened to allow representatives from the U.S. and international rock mechanics community to have a voice in this reordering.

2. Critical Areas of Research

2.1 Technical Sessions

The forum opened on October 18th with an evening session, "Stories from our Past," narrated by R. Goodman and J. Hudson. A retrospective on the career of the late Neville Cook followed, given by L. Myer. Discussion concluded with remarks concerning the attraction (or lack thereof) of rock mechanics to graduate students.

Over the next two days the following sessions were held:

1. Fractured Media; B. Amadei, host
2. Uncertainty and Scaling; H. Einstein, host
3. Imaging and Measurement; C. Barton, host
4. Fluids and Rocks; D. Elsworth, host
5. Weak Rock Engineering; R. Steiger, host
6. Catastrophic Rock Failure; C. Aimone-Martin, host
7. Research Roles of Industry; Government and Academia, S. Glaser, R. Martin, C. Schiffries, hosts
8. Role of ARMA in the Rock Mechanics Community; S. Glaser, host

2.2 Fractured Media

Rock masses are made up of geological materials that have been altered and/or broken into smaller pieces. Rock masses are by nature complex and, in general, have been subject to long and complicated geological histories. The effective rock mechanician can learn a great deal by paying attention to how time and natural processes have impacted a site, and the practitioner must have a knowledge of geology. Effects of discontinuities on rock mechanics properties include increased deformability, decreased strength, increased permeability, anisotropy, scale effects, and additional kinematic possibilities. It is clear that not all discontinuities play equal roles in the behavior of rock masses. Physically minor discontinuities and geological features may sometimes be more critical to a design than major (larger) features. These minor features, however, are often overlooked. From a practical point of view, it is not clear what represents a critical or major feature, and it is often determined in a very subjective manner.

2.2.1 Questions raised

Theoretical questions dominated the Forum discussion on fractured media, possibly reflecting that engineers do not feel comfortable with the level of theoretical understanding, even though engineers design in fractured materials as a matter of course. Questions posed included:

- Is data collected for theories that fit actual rock mass behavior, or is sampling biased by theory?
- Can the discontinuity system of a rock mass be detected, mapped, and parsimoniously represented?
- Can scale-dependent properties of a rock mass be measured and incorporated into models?
- Can behavior of fractured media be predicted at an acceptable level?
- What is the best way to represent rock mass for fluid flow and transport modeling (uncoupled or coupled)?
- Is the present understanding of coupled phenomena adequate?

2.2.2 Characterization and modeling

The behavior of fractured media is a complex problem that raises important issues of scale. Figure 2[†] illustrates a fundamental problem faced when representing a fractured medium, i.e., should fracturing be characterized deterministically or stochastically? Should the characterization of an equivalent effective medium with averaged properties, or discrete components? If models combining elements of several approaches are developed, what are the scales at which the assumptions are physically valid? Characterization of the medium has the opposite problem: if the characterization is good, the model can be deterministic, but how can the engineer determine that there is sufficient characterization? Examples of uncertainty in fractured rock models include: spatial location of critical features and fractures, discontinuity processes and locations, and rock mass geometry. Since it is impossible to find and measure every discontinuity in a fractured medium deterministically, the relationship between a measured parameter and extrapolated behavior must be used with caution.

Complicating rock mass characterization is the fact that many processes (e.g., thermal, hydraulic, chemical, mechanical, temporal, and engineering perturbations) may be coupled, and small perturbations may have large effects. Without significant simplification (linearization),

[†] Hoek, E., and Brown, E.T., (1980) Empirical Strength Criteria for Rock Masses, *Journal of Geotechnical Engineering*, 106, pp. 1013-1035.

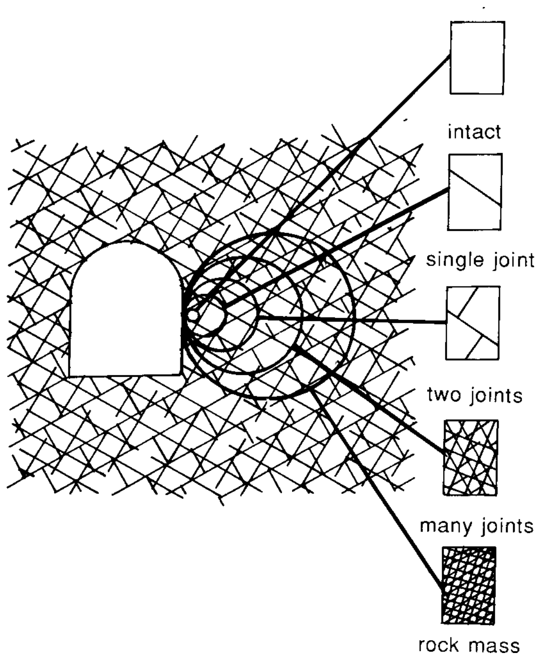

Figure 2. Concept of scale as it pertains to rock mass properties (from Hoek and Brown, 1981).

this is a very nonlinear problem, which imposes a paradigm shift in modeling and site property determination. New approaches and tools should be investigated, perhaps taken from the physics of quantum mechanics, neural networks, chaos, complexity theory, self-organized systems, and morphogenic fields. For example, neural network models appear promising, but it is not clear how directly measured physical characteristics can be derived from the arbitrary weights estimated by such models. Given these limitations, it is unlikely that rock mechanics will produce a fully coupled, deterministic, and mechanistic model. For example, in fluid flow, overlooking one conductive passage can invalidate the entire model.

From the more practical point of view taken by working consulting engineers, data are often incomplete and costly to obtain. Modelers, however, demand more data of increased variety for larger, more comprehensive models. As model complexity grows, the practitioner risks losing intellectual control, and engineering judgment may not provide independent understanding and justification. For the practicing engineer, rock mechanics modeling should provide analytical tools for gaining insight and understanding of the interplay of governing mechanisms and for exploring potential design trade-offs and alternatives, rather than as a means for making absolute predictions.

Rock mechanics has been used to successfully model, predict the behavior of, and build structures in fractured media. Behavior in response to various loading situations can be anticipated, as can interactions with the structures. All successes at modeling and construction and, more importantly, future advances are predicated on a constantly improving ability to characterize fractured rock masses. As identified at the Forum, improvements of sampling techniques and testing are of the utmost importance because the simplest model is of no use if the necessary parameters cannot be determined from field data. For rock masses, *in situ* testing is the centerpiece of site characterization needs. Our ability to test rock specimens of significant and important size is limited, and most engineering is based on results from small intact pieces of the rock mass tested in the laboratory.

2.3 Uncertainty and Scaling

2.3.1 Uncertainty

While risk and uncertainty cannot be avoided, there exist well-tempered methods for risk assessment and management. Such an approach is suggested by Figure 3, the so-called cycle of uncertainty. Since uncertainties are inherent, efforts should be made towards living with the uncertainty and incorporating it as an important part of the design process.

Uncertainties arise from a variety of sources:

- The inherent natural, spatial, and temporal variability of properties (characteristics);
- Random and systematic errors in data collection and testing;
- Model uncertainty;
- Omissions and blunders.

Many of these uncertainties are coupled. For instance, decreasing model uncertainty through a multiparameter model may lead to increased uncertainty in collecting data and testing for each parameter.

The fundamental question, therefore, is how should uncertainty be best addressed? One approach is to reduce or eliminate uncertainty and risk. In field investigations, an engineer might attempt to measure everything, which is futile. On the other hand, incorporation of uncertainty directly into the design process can be relatively straight-forward, e.g., Peck’s observational method. Conscious incorporation of the observational method with a feedback loop, as illustrated in Figure 4, allows updating of the assumed models and refinement of rock behavioral characteristics. All engineers, in fact, make constant use of the obervational method, often through invocation of engineering judgments.

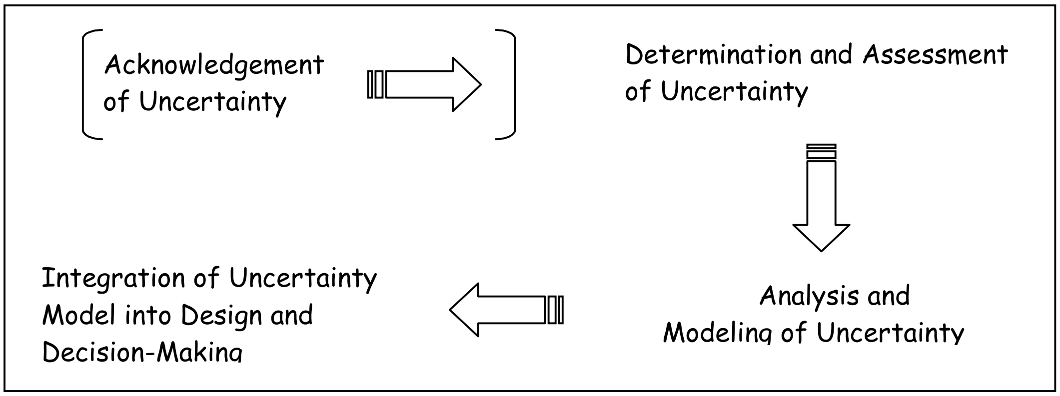

Figure 3. Cycle of uncertainty (from H. Einstein).

What is possible to accomplish in terms of field metrics is increased measurement precision and better testing and sampling techniques and plans. Most importantly, advances in site characterization through remote sensing and non-destructive testing are needed, especially to survey large areal extents and large rock volumes. Probabilistic methods may be applied directly throughout the characterization process to rationally account for scatter and inherent uncertainties of measurements and applied correlations.

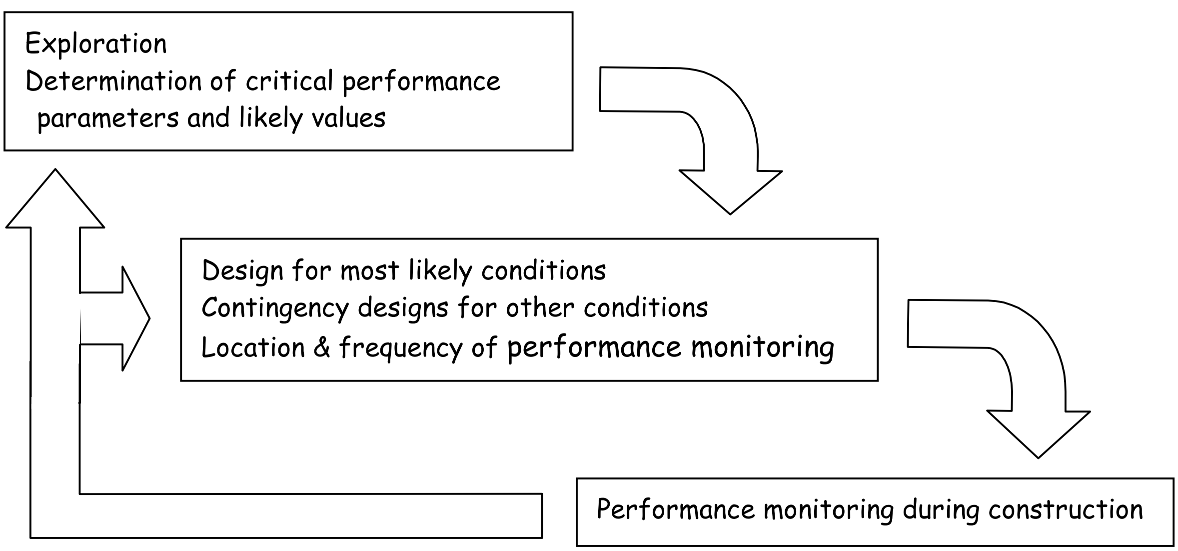

Figure 4. Observational method (feedback).

2.3.2 Conclusions for uncertainty

Procedures exist formally to incorporate uncertainties in engineering decision making, although the use of these procedures is still limited in practice. Rational implementation may be more an educational or philosophical challenge than a technical challenge. In the future, increased knowledge of *in situ* conditions may make it possible to improve measurement and modeling capabilities, somewhat reducing uncertainty.

2.3.3 Scale effects

Geology, the workplace of rock mechanics, must be addressed when developing sampling plans for site characterization, and must be incorporated during the design process. Laboratory testing to determine relevant physical parameters must reflect the geological conditions as well. Scaling relationships are an integral component of rock mass models. Transforming the physical values gleaned from tests requires scaling in time and space, and involves a degree of uncertainty since models are not exact replications of reality. For example, smaller scale processes may be inherently different from larger scale processes. Testing at the geologic scale is not always possible, so the question becomes how to use smaller scale information to determine larger scale performance.

One approach to the design of scaling relationships is to relate scaling to sources of uncertainty. For example, uncertainty exists as to the scale dependence of fracture permeability, fracture connectivity, fracture network geometry, and spatial distribution of fractures. Uncertainty also exists as to aperture dimension relation across scales and aperture variation along fracture length scales. For this approach, the best practices for micro- to macro-scale extrapolation include quantitative understanding of sampling effects, identification of limits of prediction, and placing confidence limits on these predictions. Attempts include reproducing experimental conditions comparable to reality (e.g., stress paths). Relationships between smaller scale and larger scale information could then be developed from the controlled laboratory results, either through an empirical approach, or a method based on first principles, or some combination of the two.

Another (ad hoc) view of scaling looks for correlations or “keys” that can account for size effects, rather than explicitly accounting for a change in mechanisms over many orders of magnitude of scale:

- Material strength – use of simple, general rules, such as compressive strength decrease with increasing specimen size; strain energy effects, broad application of linear elastic fracture mechanics.
- Rock mass - large fractures have predominant effect.
- Individual fracture geometry - roughness scale descriptions (Barton[‡], Rengers[§], etc.); shear resistance decreases with increasing scale of joint; flow regime changes with aperture.

One key point to consider when addressing the scalibility of mechanisms is the dichotomy between kinematics and kinetics. Generally at issue when an engineer evaluates the strength of influence associated with changes in scaling is whether the mechanisms are the same across the size scales; absolute size may not be an issue. For example, fracture toughness may be questioned as a fundamental material property, since its magnitude exhibits large variation with specimen size. This variation occurs because the distribution of flaws (mechanism) or the geometric ratios (mechanism) do not nessesarily change linearly with specimen size, not because rock fundamentally breaks differently on a site-scale than in the laboratory.

Fundamental problems exist for the ad hoc approach. Experimental conditions, such as confining stress levels, may appropriately represent *in situ* conditions, but stress distribution and sample geometry will always be different from *in situ* reality. Given inherent uncertainty as to areal distribution of physical parameters of earth materials and structures, even technically perfect sampling and laboratory procedures cannot be absolutely scaled to the field.

Scaling relationships are essentially models, thus they are also subject to uncertainty. An example of a scaling problem common to many aspects of rock mechanics is translating knowledge of microcracks to knowledge of reservoir scale fractures. Currently, it is reasonably feasible to study microfracture orientation, frequency, and permeability characteristics in the laboratory, but this is not yet possible for the field scale, the scale of most interest. Attempts to scale between the laboratory and the field using power laws and fractal dimensions have sometimes proven successful, but not always. Fractal and power laws have proven successful when the geologic mechanisms causing the studied characteristics were similar on both scales.

[‡] Barton, N. et al., (1978) Suggested Methods for the Quantitative Description of Discontinuities in Rock Masses, *International Journal of Rock Mechanics and Mining Science*s, 15, pp. 319-368.
[§] Fecker, E. and Rengers, N., (1971) Measurement of Large Scale Roughness of Rock Planes by Means of Profilograph and Geological Compass, *Proceedings, International Symposium on Rock Fracture*, paper 1-18.

When the large-scale discontinuities were formed by different mechanisms, e.g., thermal stresses locally and tectonic globally, these methods have found limited success.

2.3.4 Scaling laboratory-scale data to field applications

The following is a list of tasks that Forum participants proposed in order to improve scaling from small-scale data to large-scale projects:

- Perform large-scale tests and monitor prototype structures for design verification.
- Conduct both theoretical and field studies to determine the practicality of engineering geophysical methods for assessing *in situ* properties of the rock mass.
- Develop methods for scaling rock mass deformability and resistive properties, and permeability.
- Develop techniques to measure dynamic rock mass properties and earthquake source parameters based on centrifuge and shaking table equipment.
- Develop laboratory and *in situ* procedures for determining the thermomechanical properties of rock.
- Develop numerical techniques for estimating rock mass response to static and dynamic loads, within a probabilistic framework.
- Develop methods for assessing the *in situ* strength of rock masses.
- Develop techniques for assessing post-failure characteristics of rock masses.
- Develop techniques to assess the *in situ* condition of rock mass/reinforcement and to expand understanding of rock mass/structure interactions.

2.4 Imaging and Measurement

2.4.1 The need for site characterization

It was the unanimous conclusion from the Forum that characterization of rock mass material properties is the greatest need and the greatest challenge. All modeling, prediction, and design must have input data derived from surface or subsurface characterization. Accordingly, advances in remote sensing and non-destructive testing may be able to supply larger amounts of information from large volumes of earth, at reasonable costs. In addition to generation of pertinent input data for design, other aspects of rock engineering require improved characterization and imaging. Process monitoring, especially in circumstances involving hazardous pollutants and experimental control, are large, untapped markets for application of advanced imaging and measurement. Job close-out and verification are important needs of the geo-environmental, mining, and petroleum communities and are opportunities for the geophysics community.

2.4.2 Technologies

Geophysics allows one to rapidly measure quantities directly related to those actually needed for design over large earth volumes, which, in turn, allows one to infer the mechanical properties needed for modeling. These inferences must be based on fundamental laws of nature, which necessitates close collaboration across disciplines. Correctly using geophysical data requires accurate assessment of applicable models to choose appropriate methods, and operator experience to ensure that the field studies are correctly performed. Deficiency in either aspect may result in geophysical data with no correlation to subsurface conditions.

Near-surface imaging is mostly performed with seismic reflection and refraction. These methods can reveal major, as well as minor, geological features such as fractures, water table, and location of the capillary fringe. Interpretation of *in situ* microseismic events has been used to glean additional information about hydraulic fracture treatments. Tiltmeters have been used similarly. Increased subtlety in instrumentation and evaluation through the quantitative study of wave propagation to determine source kinematics from induced noise (damage) while pumping fractured reservoirs could yield tremendous new understandings about transient behavior of reservoirs of all types.

Borehole imaging and testing is a well-developed field due to the large infusion of research and development funding by the petroleum industry. Varieties of imaging methods include well bore and surface seismics, seismic tomography, and electrical resistance tomography. The techniques and tools are very powerful but tend to yield localized information, reinforced by detailed laboratory correlations. Parameters commonly measured include:

- Well bore stability information;
- Fracture permeability;
- Real-time data evolution;
- *In situ* stress information;
- Hydrocarbon migration;
- Fracture distribution;
- Flow location; and
- Discrimination between drilling-induced and natural fractures

Geophysical methods have many applications in oil and gas, geothermal, mining, engineering, environmental, and geotechnical industries. The future of *in situ* site characterization lies in developing multiple methods with complimentary and compounded interpretations.

Imaging tools usually generate immense volumes of data, and software development for processing such data often lags behind tool technology. Many software systems, whether commercial or in-house, require a full-time operator, have complicated licensing structures, and demand monthly maintenance and payment of use fees. In addition, no present software allows a competent user to evaluate data integrity, and standard batch processing does not ensure quality assurance or quality control (QA/QC).

Electromagnetic methods, both surface and borehole, can effectively measure degree of saturation, chemistry, and thermal properties of rock over approximately a 5 m diameter area. Ground penetrating radar (GPR) is a very promising method, the application of which is being pushed by rapid advances in equipment technology. Problems exist, such as the dielectric effects of clay minerals causing loss of depth range and interpretation problems, but these problems are rapidly being solved. Related methods include the various forms of geo-tomographic imaging. Seismic tomography has been successfully used by the mining industry to isolate dense ore bodies. In the laboratory, CAT-scans have been used to monitor core flooding in real time. Electrical resistance tomography has been used to measure accurately steam penetration in thin units during flooding, and mapping of electromagnetic emissions is a very reliable indicators of cracks with significant flow potential.

2.4.3 Geophysics and rock mechanics

Since geophysical methods provide only indirect evaluation of desired parameters, clever implementation schemes may lead to greater returns. A change in property, for instance, is much easier to measure than an absolute, ambient value. Amoco has made use of the stronger ability to measure relative changes in “reverse logging,” in which changes are measured *in situ* during well drilling, completion, and production. Combining several methods, each of which is optimal for a given parameter of interest, into a complimentary survey would result in much more accurate solutions for what, in essence, are all inverse problems.

Forum participants identified the following physical parameters as possible for measurement with geophysical tools:

- Ground conditions in front of a tunnel boring machine;
- Detection of gas- or water-filled discontinuities ahead of underground excavations;
- Quantitative measurement of rock strength, both for intact rock and rock masses;
- Thermal effects on rock properties;
- Relationship between static and dynamic elastic properties;
- Characterization of "weak" rocks such as friable sandstone or deep offshore sands;
- Location of hydrocarbon traps; and
- Conductivity measurement of fractures.

Critical obstacles to the use of well-bore imaging primarily involve cost. Sophisticated tools are needed for down-hole imaging, and sophisticated software tools are needed to manipulate and analyze voluminous bore hole data. Such sophisticated tools are expensive. Proper application of geophysics requires well-trained, experienced operators, who are at a premium, thus expensive.

Major constraints to wider spread adoption of geophysical methods are processing costs and lack of access to existent data, resulting in under-utilization of data (or non-utilization of technology). This is due in part to industry use of proprietary data formats, complicated tape access, and the unknown quality of data collected by others – a subject for QA/QC research. In competitive industries, such as oil and gas, data ownership is a fundamental issue that has yet to be solved. Access to these case histories would greatly facilitate future advances in remote imaging technology.

There is no doubt that geophysical techniques provide a double-edged sword. They offer the enticing promise of cheap, non-invasive estimation of important rock mass properties. They also hold the risk of improper interpretation, large uncertainties, and contradictory results. The two edges result from the fact that geophysics measures parameters tangentially related to the inquiry – small-magnitude properties of rock that are indirectly controlled by the parameters of interest. The promise is worth the risks and costs to develop better methodologies and equipment. We will never collect enough information by drilling holes to thoroughly characterize a site and satisfy the growing data appetite of evolving constitutive models.

2.5 Fluids and rocks

2.5.1 Flow through rock mass

Fractured rock is ubiquitous in the earth's crust. In most rock masses, fracture permeability is orders of magnitude greater than rock matrix permeability. Understanding fluid flow in rock thus requires characterizing flow in individual fractures, in fracture networks, and in heterogeneous domains of different networks. Coupled to the geometrical problem are the issues of reactive chemical transport through flow channels, effects of *in situ* stress and stress histories, thermal interactions, and biological interactions between *in situ* flora, flow channels, matrix, fluid, thermal conditions, and bio-flooding.

Fluid flow behavior in fractured rock masses has been studied intensively (e.g., *Rock Fracture and Fluid Flow*[**]), yet our ability to characterize the flow behavior of all but the most homogeneous and isotropic fractured rock masses without extensive (and expensive) site characterization and modeling remains limited. Research in fracture and fracture network flow has been advanced mostly in the petroleum and environmental industries, where economic and regulatory pressures provide funding for the research necessary to advance the state of the art.

2.5.2 Uncoupled processes

For many problems in rock mechanics, fluid flow can be modeled as an uncoupled process. The differences between uncoupled and coupled flow processes can be likened to the difference between linear and nonlinear elasticity. While it is true that the world is nonlinear (fully coupled), many interesting and important problems can be solved by taking an elastic (uncoupled) approach. Important open questions about uncoupled processes remain:

- Single phase flow & fracture hydrology
- Reactivity
- Sorption / retardation / attenuation
- Miscible displacement (transport)
- Colloid transport
- Multiphase displacement (transport)
- Short circuiting: Petroleum, Geothermal
- Fingering
- Entry pressure and path
- Characterization at scales of interest
  - Spatial
  - Temporal
- Process understanding
- Interdisciplinary reservoir genesis studies (synthesis)

** National Research Council, (1996) *Rock Fracture and Fluid Flow*; National Academy Press.

2.5.3 Coupled processes

There are at least five fundamental physical processes coupled with fluid flow: thermal, potential energy effects, mechanical, chemical, and biological processes. A change in one process will have an effect in at least one other. For example, pore-fluid chemistry may strongly affect fracture toughness, fracture healing, and osmotic behavior. Thermal variability, both spatial and temporal, also has strong effects on these processes, as well as on strength, stiffness, and slaking behavior. Characterizing and modeling coupled fluid-flow processes therefore requires an interdisciplinary approach. Research conducted by interdisciplinary teams of specialists may provide in-depth knowledge but at high monetary expense. In contrast, an individual or a very small team is much less expensive, but may not have the breadth of knowledge in all of the multitude of coupled processes needed to provide conclusive results. Funding incentives for explicitly interdisciplinary approaches to coupled fluid flow problems in rock are needed.

2.5.4 Role of faults and fractures

Faults and fracture patterns often present higher variability than discontinuities formed from purely tensile stresses. Faults may act as fluid flow conductors, and/or may provide an impermeable domain boundary. Fracture networks separated by faults may exhibit markedly different characteristics. As with other types of discontinuities, the geometry of faulting plays a large role in determining its role in fluid flow, and regional and local stresses further influence flow along faults.

The effects of faults and fractures on fluid flow are very nonlinear, hence many fundamental questions remain to be answered. For example, the influences of tectonic regimes remain to be determined, and must acknowledge the influence (or lack of influence) of the regional stresses, the local stress heterogeneities, and the *in situ* rock. Chemical and electro-chemical interactions between pore fluids and discontinuities affect fluid pressure in stable slip, stick-slip, and unstable slip (seismic triggering), as well as fault healing. Effects on fluid flow from thermal and shear coupling, jacking, and pressurization history lead to more open questions.

2.5.5 Characterization needs

Fundamental to any modeling and design work is proper characterization of the *in situ* conditions. In the context of fluid flow, the primary consideration is rock mass geometry. The critical flow features must be properly determined and parameterized for any model to be of use.

What is the geometry of the rock mass, and active flow network at depth? What are the local and global *in situ* conditions at depth (critically stressed faults are highly permeable)? What are the physical and chemical mechanisms controlling flow at depth, and their history at a particular conducting discontinuity?

The petroleum industry, in particular, has many specific characterization needs concerning fluid interaction with rock. Due to the critical role drilling fluids play in the production process, characterization of chemical coupling mechanisms with the mechanical is vital.

Note that only critical features need to be characterized, requiring thorough knowledge of the geologic context containing the underground feature, and direct interaction between the modeler and the field experimentalist, to yield satisfactory results. It was agreed that hydrologic geometry is not necessarily the same as geologic geometry, so that lacking a correct simple model, more detailed field characterization methods may be needed. Coupled fluid flow characterization involves a wide variety of physical processes. *In situ* chemistry, thermal, and other properties at depth must be measured, as well as the mechanical properties traditional to rock mechanics. Finally, the (coupled) spatial, parametric, and process uncertainties must be characterized to allow rational design and operational decision-making.

2.6 Weak *Rocks*

2.6.1 Primary tasks: identify key issues

The first task is to define what is weak rock in a more exact manner than we commonly apply to art – "I know art when I see it." Several definitions of weak rock were proposed:

- Weak rocks are rocks that have failed under their *in situ* stresses.
- Weak rocks are what they are because of where they are.
- Weak rocks are what they are relative to where they are.

Generally, weak rocks may be described as geomaterials with properties between soils and rocks.

The weak rock session of the Forum generated great interest and discussion. There was a palpable feel of excitement as the discussion touched upon technical areas of interest to Forum participants. The quantitative aspects of the discussions are summarized in table form in the next three sections.

2.6.2 Categories of weak rocks discussed at the Forum

Nature of Weakness	Cause	Example rocks
Naturally Weak	Structurally weak	Shale, mudstone, sandstone, diatomite, marl, chalk
	Evaporites	NaCl KCl, gypsum
	Organics	Coal, lignite
Chemically or mechanically altered	Tectonics	Melange
	Fault zones	Clays and gouge
	Weathering/chemical reaction	Marls, saprolite

2.6.3 Physical characteristics of weak rocks

Physical Characteristic	Associated Problems
Low ratios of strength to applied stress	failure through intact portion
Naturally occurring fractures	sliding on weak interface
Volume changes	change in effective stresses by swelling or slaking
Creep sensitive	squeezing may occur

2.6.4 Case studies as reference sites for providing characterization information

Project	Rock	Problems Encountered
• Stillwater tunnel	Red Pine Shale	fractures and fault zones, squeezing at 600m depth
• SSC tunnels and chambers	Taylor Marl	joints and weak rocks
	Eagle Ford Shale	swelling
San Antonio tunnels	Taylor Marl	joints and weak rock, fall outs over TBM
• NTS: Rainier Mesa chambers	Tuff	new fractures, joints and weak rock
• Castaic Dam	Sandstone & shale	slope failure, bedding and weak rock

2.6.5 Major issues

Squeezing ground is an important issue in civil, mining, and petroleum rock mechanics. Civil engineers are concerned about squeezing ground in tunnels and excavations. Miners are concerned about creep leading to pillar failure, mine subsidence issues, mine caving, and other problems, both underground and on the surface. Borehole stability and sanding problems plague petroleum engineers in weak rock. Challenges associated with weak rock are often exacerbated by interaction with adjacent strong rocks. Hard rock mines and tunnels may have zones of weak rocks; geologic and rock property surprises may be the rule, not the exception.

Faulting is a ubiquitous geological occurrence. Characterization of the location, and width and frequency of fault zones is vitally important to all aspects of rock mechanics practice. In addition to fault location, material properties of fault zones materials must be determined before design and construction commence. As for all characterization problems, issues of the scalability and representativeness of samples, and the ability to control sample recovery and sample disturbance are important issues that need to be addressed by future research.

Relevant characterization schemes, as well as field, laboratory, and logging techniques have yet to be developed for weak rock conditions. For example, fracture tip processes at work in weak rocks such as diatomite are poorly understood, partly because the fundamental physics are unknown. For example, stress path effects are important in weak rocks, as shown by differences in triaxial compression and extension tests. Because soft rock is ubiquitous across all disciplines of rock mechanics, analytical and experimental tools and methods could be borrowed from other disciplines such as soil mechanics, soil science, or geology. Back-analysis of unstable geostructures in soft rocks is also very important investigative tool, and deserves wider recognition.

After sufficient field measurements have been collected, the issue becomes properly classifying and modeling. When is a simple model adequate, and when should more complex models be invoked? Geology, including depositional environments, diagenesis and fracture genesis should be accounted for in models, classification and analysis of weak rocks.

2.6.6 Characterization issues: instrumentation during construction and monitoring

As for every topic discussed at the Forum, there is no universally accepted approach for *in situ* characterization of weak rock. No physical model for weak rock is accepted as broadly useful, and few models have been validated. The problem is made more difficult when there is a need to characterize and test weak rocks with fractures, very low RQD, RMR, or Q. Techniques with promise include:

- Horizontal drilling and sampling for tunnels and wells;
- Monitoring during construction;
- Inexpensive digital imaging processing programs;
- Data collection by instrumenting existing tools such as drills and shovels;
- Models for rock mass rating systems;
- Use of rock mechanics parameters specific to weak rocks in mine design software; and
- Innovative underground support design methods (yielding pillars, etc.).

2.7 Catastrophic Rock Failure

2.7.1 The issues

Catastrophic rock failure can be an intended or unintended event, i.e., a controlled or uncontrolled from an engineering point of view. The various types of failures are summarized in Table 1. Catastrophic rock failure often results in death, destruction, loss of resources, and importantly, increased public awareness induced by attention from the popular press. Publicized failures commonly occur in two settings: subsidence induced by mine collapse or rock burst, and rock slope or cliff failure. A recent (post-Forum) rock fall in Yosemite U.S. National Park, California, provides an example of the latter. Intended catastrophic events include common engineering undertakings such as excavation, mining, and blasting. It was the unanimous sense of the Forum that the ultimate goal, with respect to catastrophic rock failure, should be the development of some sort of predictive tools to mitigate loss of life and property.

Table 1. Summary of catastrophic rock failure types (from Aimone-Martin).

Failure Type		Energy Source		Failures Induced by:
Intended	Unintended	External	Internal	
Caving		Explosives	Gravity	Mining-induced stresses
	Collapse	Seismic	Gravity	Mining-induced stresses; blasting, earthquakes
	Pillar failure		Strain energy	Excessive loads on pillars
	Bumps		Strain energy	Stiff, non-yielding floor/roof
	Bursts		Strain energy	Stress concentration in hard rock, coal faces
	Slides	Excavation	Gravity	Poor drainage lowering effective stress; removal of resisting loads
Blasting fragmentation		Chemical explosives		Shear, tensile stresses; spalling
Dynamic fragmentation		Projectiles		Dynamic forces - shear, tensile

Forum participants agreed that the development and use of hybrid/coupled numerical analysis codes are relatively successful at analyzing many failure mechanisms and patterns. This ability has resulted in improved pillar, support system, and mine design. At present, however, there are few good methods for estimating surface deformations due to subterranean subsidence, quantifying magnitude and distribution of stresses, and identifying the possibility of "rare" events (those without case histories that are only represented by the geological record). At the heart of these difficulties in analyzing catastrophic failure situations is a lack of fundamental knowledge about the actual mechanics at work. For example, there is little understanding of pore collapse at extended strain and pressures above 25 MPa.

Rock is a complex, nonlinear material with memory, yet is commonly modeled as linear elastic – plastic after "failure." The full extent of coupling in the various compressive regimes where uncontrolled failures happen is not known. Consequences of poorly understood coupling mechanisms include sand production and bore failures in deep, overpressured, uncemented sands, rock bursts, and time-dependent failures of excavations – all very costly in terms of life and dollars.

Subsidence associated with abandoned mine workings is a widespread problem with significant social implications. While this problem has existed for hundreds of years, rock mechanics has a poor record of predicting the amount and distribution of surface settlement. One aspect which has led to this poor record is the lack of integration of the social issues. The industry needs to devise mechanistic as well as probabilistic design tools that incorporate economics and long-term societal costs.

2.7.2 Issues raised in discussion

The most important of the many relevant issues for increasing the understanding of mechanisms in need of future research in catastrophic rock failure include the following:

- Pore collapse: stages and mechanism;
- Non-linear elastic behavior and load-history dependence;
- Nature of failure at different burial depths;
- Time-dependence of mechanical properties and stress distribution;
- Acoustic energy sources and transmission characteristics;
- Strain energy accumulation and release; and
- Early warning systems (precursors to failure), remote prediction for improved life safety.

2.8 Research Role of Industry, Government and Academia

In the United States, national policy is changing to focus on science and technology deemed more closely related to national goals, which includes continued economic prosperity at home and abroad. Parts of this policy, under the rubric of technology transfer, has adversely affected funding for many traditional areas of research in science and engineering, including civil engineering. Although infrastructure replacement will partly mitigate this loss of available research funding, population pressures driving development to poorer quality construction sites will require creative research to meet future needs. An example is employing rock mechanics knowledge to better utilize underground space. The following reflects the discussions of Forum participants on roles of industry, government, and academia in the rock mechanics research process.

2.8.1 Private sector

The private sector plays two roles, primarily that of end-user of research, the consumers of technology developed by other organizations. In its first role, industry delivers products and services to clients, and has a need for new, more economically efficient, and environmentally friendly technologies to do so. As such, industrial representatives serve primarily as portfolio managers either of sole-source projects or as members of large consortia. The second role is that of the research organization itself.

Although no longer so common in the mining and petroleum industries, there are many basic research laboratories at firms such as IBM and Xerox. There are also a number of private research companies carrying out rock mechanics-oriented research. The size of these firms range from small (e.g., New England Research, RE-SPEC, TerraTek) to very large (e.g., Battelle Institute, Southwest Research, SAIC). As producers of new knowledge, industrial laboratories can operate as very focused units, tasked with solving a particular problem encountered by an operating unit. All research resources and personnel can be devoted to solving the problem at hand.

Independent research firms offer the additional competitive advantages of 1) relieving the client of the continued financial burden of highly specialized personnel and equipment, and 2) retaining the ability to specialize in very detailed areas that would not be cost-effective for the industrial client to do itself. Specialty firms also have the ability to complete projects rapidly. Given the immediacy of engineering research needs, however, these firms must find ways to maintain their intellectual and experimental edge while delivering services at profitable levels in fiercely competitive markets.

2.8.2 U.S. Government

Government has been a funder of research for the purpose of national defense, providing large sums of funding to industry and academia in times of perceived national need. In addition, Forum participants generally agreed that government has two major roles in the research enterprise: 1) purchaser of services, and 2) maker and enforcer of regulations to insure public health and safety. In serving these roles, the government has become the largest supporter of basic research through funding of university-based research, operation of government laboratories, and various corporate tax incentives.

Government traditionally has provided large sums of research funding to universities, contingent primarily on the scientific merit of the proposed work. Many university rock mechanics programs have grown dependent on federal funding. There are many important benefits of interest-driven research funding, since scientific research commonly produces valuable by-products. A case in point is the World Wide Web, developed by particle physicists to rapidly disseminate research results. New and controversial ideas are tested this way, resulting in many of the modern technologies we take for granted such as velcro, kevlar, and the finite element method. In addition, the national level of science and engineering education is maintained at the cutting edge, and the nation and industry benefit from a steady stream of well-educated entrants into the job market.

Recently, this model has been changing towards one of service to industry, as societal vision of the common good changes. This is especially true of the Department of Energy laboratories. These laboratories were entrusted with the production and maintenance of national security, primarily through the nuclear deterrent. In fulfilling their role, the national laboratories have made extensive contributions to rock mechanics over the past 30 years With the fall of the Soviet Union and the resultant nuclear build-down, the roles of these laboratories have had to change as well.

Government has the power to direct the main stream of rock mechanics research due to the large sums of funding it controls. In the past, this power has been generally wisely, contributing to the current state of the art. Near-term refinement of long-term goals would provide a large measure of needed stability to the current rock mechanics research environment.

2.8.3 Academia

Universities have fairly well-defined strengths and weaknesses. The primary function of the university is the creation of knowledge and intellectual capital, a function that is carried out through the education of students. At its finest, university education is much more than vocational training. Graduates learn to think for themselves and to break down "unsolvable" problems into manageable pieces.

The strengths of the university research environment are manifold and unique, and are unlikely to be duplicated by private industry. Research, with the majority of the work carried out by graduate students who work long and hard towards learning their chosen field and compiling their dissertations for little actual pay. The university administration and the public at large also support this enterprise through capital investment and low contractual overheads. Longer term projects of three years or more, anchored by a professor who serves as principal investigator, are cost effective in the university environment.

Because the ultimate end product is the education of the student, research directed in one detailed area may conclude fruitlessly, while concurrently advancing knowledge in subjects tangential to the ulterior goal. Universities also are very strong with respect to investigation of new areas. This is especially true in geotechnical engineering where unseen and unexpected site conditions end up remediated at great expense. This provides impetus for research into characterization and mitigation which are usually extremely cost-effective with respect to remediation (and litigation). Bottom line considerations may preclude private industry research of this scale and detail.

In contrast, research universities are traditionally poor at providing rapid turnaround on specific projects. Research schedules may be constrained by graduate student class schedules or their lack of previous knowledge. In many states it is not legal for publicly-assisted institutions, making use of state-subsidized labor, to compete directly with private enterprise. State-of-practice-type research will not produce new discoveries and advancements, hence dissertations, and consequently is of lesser interest to academic researchers. Secrecy is anathema to the academic community for similar reasons.

The U.S. higher education system is one of the great successes of the last 50 years. The system works well and society should thoroughly examine its needs before making major changes in the system.

2.8.4 Potential customers for rock mechanics expertise

Potential customers for rock mechanics expertise include: the oil and mining industries, construction/civil engineering in the public and private sectors, environmental engineering concerns, and military organizations, which might also find rock mechanics a useful adjunct to the engineering geology already present in military curricula. The mega-projects of the past 30 years, such as construction of large dams or urban subway systems, appear to be winding down in the United States, as is research spending by petroleum companies. Mining industry research needs tend to be driven by short-term goals, and has been well served by engineering consulting firms. During the Forum a call was made for a "focus on applications." As Figure 5 illustrates, immediate applicable results are founded on previous, leading research, which is difficult to perform concurrently with technical development. It is not at all clear whether there is currently a national will for funding leading research that provides the intellectual basis for applied

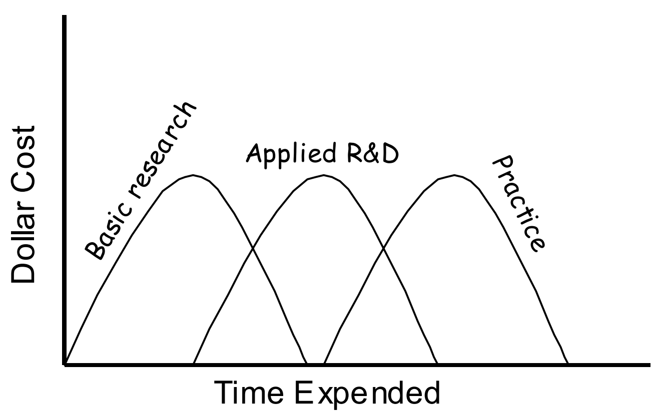

Figure 5 The progression of research and application (from H. Einstein).

research and development.

The U.S. rock mechanics community has not effectively expanded its market. The community has no lobbying presence on Capitol Hill and therefore no input into the national debate. Rock mechanics has skills needed for many national tasks (e.g., carbon sequestration, gas hydrates), but only the rock mechanics community itself seems aware of this fact. Areas of involvement at the planning stage include carbon sequestration, transportation issues, and national energy strategy. One third of DOE's budget is for environmental management, yet the issue was never raised at the Asilomar Forum. Neither were health and safety issues raised.

Why is rock mechanics playing a small role in the debate and research on the DOE carbon sequestration project? The community needs to reintegrate engineering and scientific questions so that national goals can be met. Many forum participants expressed the opinion that rock mechanics faces extinction as a discipline if this passive stance does not change.

3 Modeling issues

3.1 General Modeling Issues

The practice of rock mechanics is highly dependent on accurate observations of a material described by Richard Goodman, with accuracy and whimsy, as DIANE (Discontinuous, In homogeneous, Anisotropic, Non-linear Elastic). Data are expensive, difficult to obtain, and modelers need increasing amounts of data to build "bigger and better" models. As model detail increases, intellectual control of the model risks being lost, and engineering judgment may no longer provide independent guidance and verification. Given the constraints inherent in characterizing geomaterials, rock mechanics modeling should be used as a way to gain understanding of governing deformation and failure mechanisms, or exploring potential trade-offs and alternatives, rather than making absolute prediction. Applied rock mechanics modeling can fill the gap between practicing engineers and mathematical modelers. Experienced and well-trained engineers should have the appropriate theories and methods at their disposal to provide a range of solutions and predictions within the allocated time and budget which can provide for a safe working environment. Many models of rock behavior exist. Many ways to estimate parameters have been proposed. The need is to match appropriate methods of collecting data to the appropriate models.

3.2 Computer-Specific Issues

Proposals that address data processing and dissemination, such as data quality assurance, should be given high priority. Specifically, issues such as copyright and royalty concerns with respect to data access are becoming paramount in an age of increasing concern and litigation over intellectual property. Construction of fundamental software tools useful for rock mechanics research is useless without widely disseminating such tools. Other issues, such as data file format, may appear deceptively simple, yet lacking standard formats for data of specific interest to rock mechanics can greatly hinder collaborative research. It should go without saying that no such formats should be proprietary.

Common file formats with freely available specifications would help build knowledge and technology transfer between academia and industry. Since the advent of the Web, distributing software, data and results can be done automatically, and in near real-time. That is, ongoing numerical or laboratory results can be presented directly on the Web at the moment they are produced. Research into the appropriate guidelines for posting software, data and results on the web needs to be undertaken, possibly as a service of ARMA. Software resulting from such research should be freely available to the rock mechanics community in source form for peer review and compilation on multiple platforms.

Specification without implementation is useless, so software must be written. Software specifically addressing issues with data input and output (e.g., file formats) should be written in computer languages that are widely supported, to be useful to the largest segment of the rock mechanics community. Widely supported in this context means: 1) using computer languages that are ANSI or ISO standardized; 2) using language compilers that are inexpensive or free for most platforms; and 3) using languages that have very powerful capabilities for lexical analysis, parsing and string handling.

4 The Future of Rock Mechanics

4.1 Nontechnical Issues

The critical non-technical issue facing the rock mechanics community, noted by many of the participants, is the lack of direction for rock mechanics as a discipline in the U.S. It can be argued that this is really a corollary to a more fundamental issue: rock mechanics does not widely enjoy the privilege of recognition as an independent scientific and engineering discipline. Rock mechanics meets the criteria of an independent discipline within science and engineering, characterized by three basic activities: observation of physical (rock) systems, analysis of those systems (analytical and numerical), and prediction using laboratory experiment and numerical simulation. Although these may be statements of the obvious to practitioners in the field, they may not be at all obvious to industry and academic employers, and to the agencies considered as funding sources.

To insure survival of rock mechanics as an independent discipline, the following recommendations are presented:

1. Practitioners should sell services from a rock mechanics perspective; educate clients (academic, industrial, governmental) to the economic benefits resulting from the interdisciplinary nature of rock mechanics research and practice.
2. Civil, mining, and petroleum industry practitioners of rock mechanics should take steps to present an integrated program for rock mechanics education.
3. Industry/academic research efforts should have technology transfer components.

A rock mechanics researcher can serve as a useful bridge between fields as diverse as geology, civil engineering, mathematics, and computer science. What U.S. rock mechanics needs possibly more than anything else, are strong, persuasive champions.

4.2 Role of Research in Addressing the Critical Issues

From a technical standpoint, rock mechanics has been successful. First order models useful for a large range of industrial and design applications have been accepted and used with success by practitioners. Pioneers of the 1960's and 1970's provided a strong foundation for future research activity. Future advances, however, will require more accurate models incorporating non-linear and coupled behavior. Currently, it is not possible to measure parameters needed for such models. Without accurate methods of evaluating rock mass parameters, these models of the future will not benefit the profession.

As examples of the types of problems that rock mechanics has successfully answered through research and development, the forum compiled a list of the most important advances made to date:

1) Rock mass classification; quantification of geologic parameters; behavior of microstructure fracture permeability; effect of discontinuities on seismic wave propagation; use of geophysical tools to solve rock mechanics problems; development of tools to measure rock properties in the field; understanding of rock blocks; rock-structure interaction; kinematics and structural features at all scales; collaboration and exchange between researchers.

2) Coal pillar design; support of underground mine openings; design methods for surface interfaces; recognition of well-bore breakouts; hydraulic fracturing; tunnel boring machines; failure of holes.

3) Sophistication of numerical modeling for rock mechanics; discontinuity analysis; numerical simulation technologies; effective stresses and poroelasticity; microfracturing; coupled

processes; applied fracture mechanics; development of failure theories; micromechanisms of failure; understanding pore structure models; stability/instability; post-failure brittle analysis.

4.3 Role of ARMA

4.3.1 Key questions and goals

There are two fundamental questions that must still be answered before ARMA can reach its potential as a member-based organization serving the needs of the membership: "What goals can we the rock mechanics community agree are the most important to us all?" "Are we willing to work together towards these goals?"

A few future services ARMA could provide were proposed at Asilomar:

- An automated integrated repository for rock and rock mass data;
- Integration of the geologic context into rock mechanics design;
- Integration of geophysics into the practice of rock mechanics;
- A national rock mechanics test site;
- Classification scheme for soft rock;
- *In situ* characterization, especially of discontinuities;
- Joint ARMA-USNC/RM advisory panel for government initiatives;
- Task force on environmental rock mechanics; and
- "Optimization of limited resources."

4.3.2 Developing a strong presence in other organizations

ARMA currently has liaison relationships with the following rock-related organizations. Liaison activities have are already led to joint sessions, short courses, and conferences with SPE and ASCE-GI. What is needed is further insight and ideas about what to do with these contacts.

- American Association of Petroleum Geologists
- Association of Engineering Geologists
- American Institute of Professional Geologists
- American Society for Testing and Materials
- American Underground Construction Association
- Geo Council
- Geo-Institute of American Society of Civil Engineers
- Geological Society of America
- Society of Explosives Engineers

- Society of Mining Engineers
- Society of Petroleum Engineers
- United States National Committee for Rock Mechanics
- Water Jet Technology Association

5. Conclusions

The 1999 ARMA Forum convened at Asilomar California to address four issues: 1) development of a strategic vision for the future of rock mechanics in the United States; 2) identification and delineation of critical issues facing the rock mechanics community; 3) the role of research in addressing these issues; and 4) identification of critical areas of research in each of the topic areas addressed including examples of specific research initiative. The Forum successfully met goals 2, 3 and 4. Rock mechanics in the United States has many technical challenges remaining, requiring significant research time and money. The primary goal, that of defining a strategic vision of rock mechanics in the United States, was less than adequately addressed, attendees found it easier to talk about the past and present than about the future.

The practice of rock mechanics and rock mechanics research in the United States stands today at a crossroads. The research climate of the previous 30 years is changing rapidly, a result of changes in corporate, governmental and academic roles. Although certain aspects of the discussion at Asilomar highlighted pessimism with respect to today's undeniably more challenging research climate, the formal recognition that rock mechanics must adapt to survive may be the single most important positive result of the meeting. The interdisciplinary nature of rock mechanics problems and the training required to solve such problems are valuable to the scientific, engineering and social communities at large. Survival of rock mechanics in part means promoting rock mechanics along interdisciplinary lines. To this end, the rock mechanics community should take a cue from the apparent difficulty of the rock mechanics endeavor: rock is a difficult and confounding material. Maintaining and growing the U. S. rock mechanics community built by today's retiring pioneers may prove no less difficult and confounding; there is no silver bullet.

6 Acknowledgements

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Appendix 1 Feedback From Participants

A feedback questionnaire was distributed among 48 attendees; 18 were returned with comments. The overall response was positive. The questionnaire consisted of four questions, with room for further comments, which are summarized below. Two outliers were discarded: one respondent liked the wine and cheese social, and nothing else, another respondent liked everything and found no room for improvement!

A1.1 What Was Good?

Most attendees who responded enjoyed the "open discussion" format, and appreciated the breadth of interdisciplinary subject material. The presence of recognized leaders in the rock mechanics community was notable and appreciated. One respondent commented on the "cross-cultural" communication; another on the "excellent diversity of people." The forum facilities at Asilomar were also well-liked: the venue was isolated from distracting activities, but with an informal ambiance that stimulated discussion.

A1.2 What Was Not-So-Good?

Asilomar was the first forum for ARMA, and several areas were noted that could be improved for future efforts. First among suggestions was to strictly enforce limits on session presentations, to allow much more time for discussion. Some respondents felt that sessions were too easily dominated by presentations of personal work and research.

A1.3 What Needs Improvement

The most critical comment, in every sense of the word critical, was that ARMA needs to provide "more active and stronger leadership." Some felt that there too many sessions for the allotted time, and that reducing the number of sessions would allow more discussion. A perceived absence of the tectonophysics and environmental communities was noted, and it was suggested that ARMA make overtures to these communities.

A1.4 Subjects for future Forums

Two types of subjects were suggested for future discussion: general forums focusing on education, interdisciplinary research, and the role of ARMA; and forums of restricted scope dedicated to specific subject areas including fractured media, mining engineering problems, failures, rock mechanics applications/design, and coupled processes.

Appendix 2 Attendees

Catherine T. Aimone-Martin
New Mexico Inst. Mining and Technology
Socorro, NM

Bernard Amadei
Vice President, ARMA
University of Colorado, Boulder

Colleen Barton
GeoMechanics International, Inc.
Palo Alto, CA

James Ching
Dept. of Civil Engineering
University of California, Berkeley

Koon Meng Chua
Dept of Civil Engineering
University of New Mexico

Edward J. Cording
University of Illinois, Urbana

F.H. Cornet
Institut de Physique du Globe de Paris
Paris 05 France

Wolfgang Deeg
Duncan, OK

Thomas Doe
President, ARMA
Golder Associates, Inc.
Redmond, WA

David Doolin
Dept. of Civil Engineering
University of California, Berkeley

Herbert H. Einstein
Vice President, North America, ISRM
Massachusetts Institute of Technology

Derek Elsworth
Penn. State University
University Park, PA

Albert Essiam
Dept. of Civil Engineering
Massachusetts Institute of Technology

Russell Ewy
Chevron Petroleum Technology Company
San Ramon, CA

Steven Glaser
Secretary, ARMA
University of California, Berkeley

Richard Goodman
Mendocino, CA

Keith A. Heasley
National Inst. Occupational Safety & Health
Pittsburgh Research Laboratory

Kristina Hernendez
Dept. of Civil Engineering
University of California, Berkeley

Francois E. Heuze
Lawrence Livermore National Laboratory

L. Brun Hilbert
Exponent, Failure Analysis Assoc.
Menlo Park, CA

Sarah Holtz
Dept. of Civil Engineering
University of California, Berkeley

Haiying Huang
University of Minnesota

John A. Hudson
Welwyn Garden City
Herts AL8 6SG, United Kingdom

Violeta M. Ivanova
Schlumberger Inc.
Austin, TX

Evandro Jimenez
University of Illinois
Urbana, IL

John Kemeny
University of Arizona

Mohamad Khodaverdian
Baker Oil Tools
Houston, TX

P.H.S.W. Kulatilake
University of Arizona

Paul R. La Pointe
Golder Associates, Inc.
Redmond, WA

Stephen E. Laubach
Bureau of Economic Geology
Austin, TX

Wunan Lin
Lawrence Livermore Laboratory
Livermore, CA

Randall Marrett
University of Texas, Austin

Randolph J. Martin
New England Research, Inc.
White River Junction, VT

Fersheed K. Mody
Baroid Corp.
Houston, TX

Navid Mojtabai
New Mexico Inst. Mining and Technology
Socorro, NM

Larry R. Myer
Lawrence Berkeley National Laboratory

Robin Newmark
Lawrence Livermore National Laboratory

Kalman Oravecz
New Mexico Inst. Mining and Technology
Socorro, NM

William G. Pariseau
Member of the Board, ARMA
University of Utah

Jean-Claude Roegiers
Treasurer, ARMA
Rock Mechanics Institute
Norman, OK

Saeid Saeb
Rocksol Consulting Group, Inc.
Boulder, CO

Craig Schiffries
Board on Earth Sciences and Resources
National Academy of Sciences
Washington, DC

Peter H. Smeallie
Executive Director, ARMA
Alexandria, VA

Donald W. Steeples
University of Kansas
Lawrence, KS

Ronald P. Steiger
Exxon Production Research
Houston, TX

Irving Studebaker
Federal Way, WA

William Warfield
Roseville, CA

Nicholas B. Woodward
U.S. Department of Energy
Germantown, MD

Mark D. Zoback
Stanford University