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Bernard Amadei and Peter Smeallie, Principal Investigators

Workshop on Industry-Government-University Partnership in Rock Mechanics and Rock Engineering: Challenges and Opportunities

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Written By:

Bernard Amadei
Professor, Dept. of Civil, Environmental and Architectural Engineering
University if Colorado, Boulder CO 80309-0428

Peter Smeallie
Executive Director, American Rock Mechanics Association
600 Woodland Terrace, Alexandria VA 22302

François E. Heuze
Lawrence Livermore National Laboratory
Livermore CA 94550

ARMA
AMERICAN ROCK MECHANICS ASSOCIATION

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Workshop on Industry-Government-University Partnership in Rock Mechanics and Rock Engineering: Challenges and Opportunities

Executive Summary

The workshop entitled "Industry-Government-University Partnership in Rock Mechanics and Rock Engineering: Challenges and Opportunities" (IGU workshop) was held on June 6, 1999, prior to the 37th US Rock Mechanics Symposium in Vail, Colorado.

The objectives of the IGU workshop were to develop a consensus among industry, government and university participants on the future course of education and research in rock and to prepare an action plan with strong and realistic recommendations for future collaborative work. These objectives were addressed by bringing together three groups of individuals: senior executives from corporations and firms in the private practice of rock mechanics and rock engineering, representatives of various federal agencies, and educational leaders interested in various aspects of rock mechanics and rock engineering. Altogether, the workshop provided a "meeting of the minds" and brought together participants with diversified backgrounds.

In general, the workshop participants reached encouraging conclusions with regard to the role that rock mechanics has played and is still playing in industry. Two conclusions are worth noting:

- It is clear that the rock mechanics and rock engineering community in the U.S. is alive and well. Although the priorities and the professional and economic climate may not be the same as they were 20 or 30 years ago, rock mechanics is needed today more than ever in a wide variety of projects faced by the mining, civil, and petroleum industry.

- To a large degree, rock mechanics has been used successfully to model and predict the behavior of fractured rock masses. Tools and models have been developed that are useful for a large range of industrial and design applications. The tools may not be complete but they provide workable solutions. The tools can always be refined.

Rock mechanics is evolving in a professional and economic climate with priorities that are quite different from those of the 1970s and 1980s. Industry is operating in a more competitive marketplace where quick returns are expected, and benefit margins that were often used for research and development (R&D) are now limited. Government has been strongly affected by downsizing and restructuring. Finally, on the academic side, rock mechanics research has become increasingly constrained by reduced government support and short-term objectives by industry. Limited funds exist to support graduate work, fewer graduate students are available, and many universities have redefined themselves as research universities. The 1990s have also seen a reduction in state funding for higher education from 15-16% in the early 1980s to 9-10% in the mid-1990s.

Another element to consider in future collaborative work is the global nature of the problems that society is facing today. Issues of national interest such as waste management, infrastructure development and rehabilitation, construction efficiency and innovation, national security, resource discovery and recovery, mitigation of natural hazards, frontier exploration and development, and sustainable technologies are expected to carry well into the next century.

Despite the global nature of today's problems, rock mechanics and rock engineering has remained divided into disciplines such as mining, civil, and petroleum engineering, geology, and geophysics. These disciplines have traditionally evolved on their own without much cross over between them. They have been very creative in their growth but have come of age and are now stagnating.

Also, despite its many technical contributions to society, rock mechanics has not effectively expanded its markets and publicized its contributions. As a result, rock mechanics does not widely enjoy the privilege of recognition as an independent scientific and engineering discipline, and it is often seen as a low-tech domain. It is poorly known to the general public, to political and economic groups, and to other branches of engineering.

The survival of rock mechanics means promoting rock mechanics along interdisciplinary lines, exploring new global markets, breaking the traditional internal divisions, and developing collaborative partnerships. The workshop participants strongly believed that partnerships between academia, industry and government agencies can provide win-win benefits to all parties involved and to society at large. More specifically, (1) Partnerships provide ways of integrating research and education into the real world of design and construction, (2) Industry/government partners benefit from faculty and student expertise, access to university laboratory, computing and library resources. In return, university partners benefit from the experience and expertise of industry/government partners with management, marketing, design, installation, and performance monitoring, (3) Partnerships provide new venues and opportunities for researchers and educators to become more aware of industry's real problems, and (4) Partnerships allow educators and students to be exposed to real case studies, to gain appreciation for the importance of applying fundamentals to solve practical problems, and ultimately to gain first hand practical experience through research, sponsorship or internships. As a result, students develop better technical and communication skills, an enhanced learning experience and are better prepared to enter the workforce upon graduation.

Finally, it is clear that ARMA can play a critical role in the future in developing collaborative work in rock mechanics and rock engineering in the U.S. Partnership or consortium development fits well within the overall mission of ARMA. ARMA can serve as an intermediary between industry, government and academia. It can work with industry to develop goals and help the civil, mining and petroleum industry to achieve their own respective goals. ARMA can also bring awareness to industry and build partnerships in response to industry/government needs. Once the needs are identified, ARMA can help select the most appropriate partners and create task forces. Finally, ARMA can also serve as a clearinghouse for rock mechanics R&D funded by practice and academia.

1. Introduction

The American Rock Mechanics Association (ARMA) organized a workshop entitled "Industry-Government-University Partnership in Rock Mechanics and Rock Engineering: Challenges and Opportunities" prior to the 37th US Rock Mechanics Symposium in Vail, Colorado. The workshop, also referred to as the "IGU workshop" throughout this report, was held on June 6, 1999.

The objectives of the IGU workshop were to develop a consensus among industry, government and university participants on the future course of education and research in rock mechanics and rock engineering and to prepare an action plan with strong and realistic recommendations for future collaborative work. The objectives of the IGU workshop were addressed by bringing together three groups of individuals: senior executives from corporations and firms in the private practice of rock mechanics and rock engineering, representatives of various federal agencies, and educational leaders interested in various aspects of rock mechanics and rock engineering.

The organizers of the IGU workshop felt that such a meeting was indeed necessary as our world approaches the dawn of a new century and millennium. The last comprehensive study emphasizing the role of rock mechanics in a number of national issues was conducted by the Geotechnical Board of the National Research Council in the late 1980s. The report published in 1989 and entitled "Geotechnology: Its Impact on Economic Growth, the Environment and National Security" clearly emphasized the critical role played by geotechnology (rock and soil mechanics) in the modern world. Figure 1, extracted from this report, shows the ramifications of geotechnology. It is clear that a wide range of disciplines involve soils and rocks and contribute to geotechnology.

The IGU workshop provided a "meeting of the minds" and brought together participants with diversified backgrounds. It showed that the multi-disciplinary aspect of rock mechanics is still strong today. The workshop confirmed that rock mechanics and rock engineering play a significant role in issues of national interest such as waste management, infrastructure development and rehabilitation, construction efficiency and innovation, national security, resource discovery and recovery, mitigation of natural hazards, frontier exploration and development, and sustainability and sustainable technologies. These issues, identified in the 1989 report of the Geotechnical Board, are still valid today and are expected to carry well into the next century.

However, it is clear that rock mechanics is evolving in a professional and economic climate with priorities that are quite different from those of the 1970s and 1980s. The survival of rock mechanics means promoting rock mechanics along interdisciplinary lines, exploring new global markets, breaking the traditional internal divisions, and developing collaborative partnerships. Active collaboration between industry, government and universities along with technology transfer and synergy between theory and practice are required. ARMA can play a critical role in the future in developing collaborative work in rock mechanics and rock engineering in the U.S.

Figure 1: Scientists and Engineers in Geotechnology draw upon many disciplines to solve their problems

Scientists and Engineers in GEOTECHNOLOGY

GEOLOGY & ENGINEERING GEOLOGY
- Exploration
- Characterization

PHYSICS
- Weapons effects/ground motion

PUBLIC POLICY
- Research policy/funding

MINING ENGINEERING
- Mine design/stability
- Mine wastes
- Land reclamation

PETROLEUM ENGINEERING
- Stimulation of oil and gas reservoirs

MECHANICAL ENGINEERING
- Drilling and excavation
- Support
- Instrumentation

GEOPHYSICS
- Exploration
- Characterization
- Diagnostics

COMPUTER SCIENCE
- Code development/ software engineering

GEOCHEMISTRY
- Waste isolation

SEISMOLOGY
- Ground motion predictions

GEOHYDROLOGY
- Fluid flow
- Waste isolation

CIVIL ENGINEERING
- Construction
- Rock mechanics
- Soil mechanics
- Structural analysis

2. Background

2.1 The American Rock Mechanics Association (ARMA)

In 1994, the American Rock Mechanics Association (ARMA) and the ARMA Foundation were created to respond to the needs of the rock mechanics and rock engineering community and to promote dialog and exchange between academia and practice. ARMA is the first membership organization for U.S. rock mechanics. The ARMA Foundation is the nonprofit educational organization for rock mechanics. Both the ARMA and the ARMA Foundation were formed as an outgrowth of concern that rock mechanics in the U.S. needed revitalization, with greater involvement of the professional community concerned with applied rock mechanics.

Since 1994, ARMA has been developing a variety of means for serving the needs of the rock mechanics community. Several meetings have been organized to involve practice to a greater extent and promote academia-government-industry cooperation and dialog. In 1998, ARMA organized a forum entitled “New Directions for U.S. Rock Mechanics.” This NSF-sponsored forum was held at the Asilomar Conference Center in Pacific Grove, California, from October 18-20, 1998. The event addressed client-driven technical challenges in rock mechanics and rock engineering and outlined some new directions for the practice of rock mechanics and rock engineering in the U.S.

The Asilomar forum was followed by the workshop entitled “Industry-Government-University Partnership in Rock Mechanics and Rock Engineering: Challenges and Opportunities” which is the subject of this report. Also, beginning in 1999 with the 37th U.S. Rock Mechanics Symposium in Vail, Colorado, ARMA took over primary responsibility for the annual U.S. Rock Mechanics Symposium and the biennial North American Rock Mechanics Symposium.

Since the mid-1950s, the U.S. Rock Mechanics Symposium has been an important forum for the rock mechanics and rock engineering community. This annual event brings together professionals and practitioners from academia, industry and government, primarily from the United States. A growing number of participants are from foreign countries. The symposium has always been a forum where new ideas and R&D results are presented, latest technical and educational developments are exhibited, old friendships are renewed, and new ones are created.

Over the past five years, we have a witnessed a marked decrease in participation from industry and federal agencies in U.S. Rock Mechanics Symposia. A recent survey conducted by ARMA shows that attendance in previous years consisted of 27 percent from private industry, 45 percent from academic/research institutions, and 28 percent from government agencies. Several factors have contributed to the reduction in industry and government participation: financial constraints, reorganization and restructuring of federal agencies and the private sector, no clear efforts of cooperation between research and practice, and a perception that the US. Rock Mechanics Symposia have become too academic and of limited benefit to practice.

In organizing the 37^{th} U.S. Rock Mechanics Symposium and the IGU workshop and in scheduling those two events back-to-back, ARMA's intent was to bring practitioners side by side with researchers and promote interactions and dialog between representatives of the various disciplines of rock mechanics. Both events were designed in the spirit of creating synergy between theory and practice.

2.2 Vail Rocks '99

The 37th U.S. Rock Mechanics Symposium (also known as *Vail Rocks '99*) was the first U.S. Rock Mechanics Symposium organized and managed by ARMA and the ARMA Foundation. The symposium took place from June 6-9, 1999, at the Marriott's Mountain Resort in Vail, Colorado.

The theme of the symposium was "Rock Mechanics for Industry." The symposium was attended by 384 participants and consisted of 5 keynote lectures, 32 sessions, and 2 sessions on retrospective case histories. The symposium proceedings were published by Balkema and consisted of two hardbound volumes with a total of about 1,250 pages representing 158 technical papers. The highlights of the symposium included:

- Presentation of latest laboratory and field research and development results, and how these developments are of benefit to industry.
- Case history sessions dedicated to significant on-going rock mechanics projects in civil, mining, petroleum, and geological engineering.
- Retrospective case history sessions of past projects by respected practitioners. What have we learned in the past 30 years? How would we do things differently today? How has industry evolved?
- Presentation of new developments in equipment, software, and technology; technology transfer from research to practice. How can industry take advantage of these new developments?
- An exhibit with 20 exhibitors presenting the latest developments in testing equipment, laboratory and field instrumentation, software, products and engineering services.
- Site visits to various civil engineering and geologic landmarks in the Rocky Mountains of Colorado.

In addition to the technical sessions, which represented the main activity at *Vail Rocks '99*, several pre-symposium conferences, workshops and short courses were offered to the symposium participants. In addition to the IGU workshop, others were:

- Technical Auditing of Rock Mechanics Modeling and Rock Engineering Design
- Finite Elements in Geomechanics
- Rock Mechanics Applications of Borehole Geophysics
- Key-Block Analysis
- Latest Advances in Hydraulic Fracturing
- The 2nd International Workshop on Coal Pillar Mechanics and Design
- The International Workshop on Rock Mechanics of Nuclear Waste Repositories
- The 3rd International Conference on Analysis of Discontinuous Deformation (ICADD-3)

Overall, *Vail Rocks '99* and the various pre- and post-symposium events were well received by the participants. The organizers of *Vail Rocks '99* and the ARMA board felt that they had met their main goal in bringing the rock mechanics community back together and in re-opening the dialog between research and practice.

2.3 Asilomar Forum

The conclusions reached from the Asilomar forum were important in designing the overall agenda of the IGU workshop. The objectives of the forum were fourfold:

- Develop a strategic vision for the future of rock mechanics in the U.S.,
- Identify and delineate critical issues facing the rock mechanics and rock engineering community today,
- Identify the role of research in addressing these issues, and
- Identify and address critical areas of research.

The forum attracted 49 participants representing a wide variety of practitioners in the civil, mining and petroleum industry.

The forum was organized into eight consecutive interactive sessions on subjects that were felt of importance to the rock mechanics community: fractured media, uncertainty and scaling, imaging and measurement, fluids and rocks, weak rock engineering, catastrophic rock failure, research roles of industry, government and academia, and role of ARMA in the rock mechanics community.

In general, the forum participants reached encouraging conclusions with regard to the role that rock mechanics has played and is still playing in industry. Two conclusions are worth noting.

1. It is clear that the rock mechanics and rock engineering community in the U.S. is alive and well. Rock mechanics is needed today more than ever in a wide variety of projects faced by the mining, civil, and petroleum industry. The multi-disciplinary aspect of rock mechanics shown in Figure 1 is still valid today. Its contributions to industry and society in general are expected to carry well into the next century.

2. To a large degree, rock mechanics has been used successfully to model and predict the behavior of fractured rock masses. Tools and models have been developed that are useful for a large range of industrial and design applications

Despite encouraging trends, improvements on present success are needed. The forum participants identified several critical areas which are regrouped below into five categories.

2.3.1 Rock Mass Characterization and Modeling

Rock masses are by nature complex and have been subject to long and complicated geological histories. Practitioners and researchers can learn a great deal by paying attention to how time and natural processes have impacted a site. More than ever, rock mechanics practitioners must have a good knowledge of geology and be able to identify geological processes and geologic hazards.

In general, rock masses are discontinuous, anisotropic, and heterogeneous. Their properties are scale dependent in both time and space. Complicating rock mass characterization is the fact that many natural processes (thermal, hydrological, chemical, mechanical, biological) are coupled. The characterization (laboratory and field) and the modeling of coupled phenomena are, in general, difficult due to the non-linearities involved.

Despite advances in computer and information technology and the availability of advanced two-dimensional and three-dimensional computational tools, many unanswered or partially answered questions still remain. What constitutes an acceptable prediction of rock mass behavior? What constitutes an acceptable characterization of intact rock and discontinuity properties? How the scale dependency of rock mass properties can be incorporated in models? How adequate our understanding of coupled phenomena is? What represents major and minor geological features at a project site?

Because of rock mass characteristics, it is unlikely that rock mechanics will ever be successful in producing a fully coupled deterministic and mechanistic model of rock masses. Rock masses resemble more chaotic open dissipative systems than well behaved and organized closed non-dissipative Cartesian systems. New fields of sciences such as quantum mechanics, complexity, chaos theory, neural network and fuzzy theory may provide new radical ways for rock mass characterization and modeling.

If rock masses behave as chaotic systems, then according to chaos theory, they cannot be controlled or predicted. Likewise, it not possible to collect all the information about a rock mass. However, models (physical, numerical) can be used as a way to gain understanding of governing deformation and failure mechanisms, or exploring potential tradeoffs and alternatives rather than making absolute predictions. Models also allow making changes in the input data to see how the changes affect the overall response. Being able to acquire engineering judgment using models is critical when developing, for instance, predictive tools to mitigate loss of life and property associated with catastrophic rock failure such as rock bursts, slides, bumps, pillar failure, subsidence and mine caving.

2.3.2 Data and Uncertainty

With the recent progress in information technology data on rock masses and on rock-structure interaction. However, there are still questions, it is now possible to collect large amounts of regarding what constitutes important data to a given project, and the quality control of the data. That appreciation is not often taught to young engineers and is not clear in practice.

It should also be made clear that large amounts of data do not always remove the uncertainty problems that are inherent in the characterization, modeling and analysis of rock masses: uncertainties in the material itself, uncertainties in data collection and testing, and uncertainties in model prediction. Fuzzy logic theory reminds us that the more closely we examine a complex problem, the fuzzier its solution is likely to be. As complexity arises, precise statements lose meaning and meaningful statements lose precision.

Efforts should therefore be made to include uncertainty rather than to try to avoid it and eliminate it. Procedures derived from the field of probability, statistics, and risk analysis exist to incorporate uncertainties in engineering decision making. However, the use of these procedures is still limited in rock engineering practice.

2.3.3 Weak Rocks

The classical division between rocks and soils and the emerging fields of rock and soil mechanics have left behind a whole range of geological materials that are sometimes called stiff soils or weak rocks. It turns out that practice is often faced with such materials. For instance, squeezing ground is an important issue in civil, mining and petroleum engineering.

There seems to be a consensus that weak rocks are still poorly understood in engineering practice. Their classification is loosely defined. Furthermore, they are difficult to characterize, sample, test and predict.

2.3.4 Geophysics and Non-Destructive Techniques

A wide spectrum of geophysics and non-destructive techniques are available to characterize rock masses in a non-invasive manner. Remote sensing, near-surface imaging, borehole imaging, and non-destructive testing methods can supply large amounts of data at reasonable costs. Such techniques usually sample large volumes of rocks comparable to those involved in rock-structure interaction. Therefore, such techniques represent valuable tools in engineering practice.

One of the major limitations of geophysics and non-destructive methods lies in the processing of the data generated. Software development for processing such data often lags behind tool technology. Furthermore, no present software allows for competent users to evaluate data integrity and no procedure is available to ensure quality assurance and quality control (QA/QC). Other limitations are related to the costs involved in processing data, the difficulty of access to the data due to their traditionally proprietary nature, and the cost of the more specialized personnel required to conduct the tests and analyze the data.

2.3.5 Professional and Economic Climate

Rock mechanics is evolving in a professional and economic climate with priorities that are quite different from those of the 1970s and 1980s. The players (industry, academia and government) are essentially the same, but the rules of the game have changed. For instance, 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 U.S. as is research spending by petroleum companies. Mining industry research needs tend to be driven by short-term goals that have been well served by engineering consulting firms.

Contributing to the 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. High-paying jobs attract students to industry, while limited funds exist to support graduate work. Meanwhile the private sector, notably mining and petroleum, has undergone severe restructuring which has strongly altered the climate in industrial research. The benefit margins that were used for R&D are quickly shrinking and are often used for information technology and employee development. 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 concluded with an overall discussion on possible future collaboration between industry, government and academia in the field of rock mechanics and rock engineering. It also discussed the role of ARMA in facilitating such collaboration. As such, the forum provided the foundations for the IGU workshop.

3. IGU Workshop

3.1 Format

The IGU workshop took place on Sunday June 6, 1999 from 8:00 a.m. to 5:00 p.m. at the Marriott's Mountain Resort in Vail, Colorado. Mr. Peter Smeallie, executive director of ARMA and Dr. Francois Heuze from the Lawrence Livermore National Laboratory were the workshop co-chairs. Ms. Robin Amadei from Common Ground Mediation facilitated the workshop discussion. The workshop discussion was transcribed by Ms. Pam Hansen from Blando Reporting & Video Service, Inc. Appendix A gives the workshop agenda.

A panel of 10 invited speakers was selected to cover a wide range of interests in the practice of rock mechanics and rock engineering in the civil, mining and petroleum industries. The list of invited speakers can be found in Appendix B. The workshop had an open forum format and involved strong interaction among participants.

The workshop addressed several key questions:

- What role does rock mechanics play in the mining, civil and petroleum industries?
- What are the industry needs in rock mechanics education and research? How should engineering education respond to those needs in an environment of rapid change?
- How should we teach the practice of rock engineering in a university system that becomes more focused on research?
- What new trends are emerging in rock engineering?

Further questions about possible partnerships included:

- How do we bring students, faculty and administrators closer to the real world through teaching of engineering practice?
- How do we bring practitioners into the classroom and into research institutions?
- Is team teaching of rock mechanics with inter-mixing of academic and practice feasible?
- How do we bring faculty with limited experience closer to practice?

The workshop started with the panelist presentations. This was followed by plenary discussions and work in small groups. The small group discussions helped in addressing the partnership needs in the separate fields of mining, civil, and petroleum engineering. The workshop concluded with an overall action plan.

3.2 Questionnaire

In preparation for the actual workshop, a questionnaire was sent to about 125 industry representatives involved in rock mechanics and rock engineering (RMRE) in the U.S. The questionnaire consisting of four basic questions:

- What has RMRE done for your company or your clients in the past? Please be specific as to the technical aspects.
- What RMRE problems have not been solved?
- What RMRE problems do you face now or anticipate facing over the next decade with which you will need help?
- What are your suggestions on how to build a partnership among industry, government and academia to help solve those problems? Please be specific about topics such as training, curriculum, funding mechanisms, and so forth.

About 20% of those contacted responded to the questionnaire. The answers to the questionnaire served as a starting point for conducting the workshop. They were analyzed and made available to the workshop panelists. The answers were also presented at the start of the workshop and integrated into the panelists presentations.

3.3 Successes

The workshop reinforced the positive conclusions reached at the Asilomar forum. In particular, there was a consensus among those who responded to the questionnaire, the panelists and the workshop participants that rock mechanics has been successful in addressing specific problems of interest to the mining, civil and petroleum industry. Because of rock mechanics, it has been possible to successfully design, build, construct and operate projects in a wide variety of geologic conditions.

It is clear that all rock mechanics problems are far from being completely understood. However, we now have tools and models that provide workable yet incomplete solutions. Such solutions have been found useful for a wide range of industrial and design applications. More specifically, successes were reported in the following areas:

General: Better understanding of intact rock and rock mass behavior; formal consideration of uncertainty; better knowledge of swelling and squeezing rocks; rock mass classification systems; quantification of geologic parameters; behavior of microstructure; fracture permeability; effects of discontinuities on seismic wave propagation; use of geophysical tools to solve rock mechanics problems; development of tools and techniques to measure rock and rock mass properties in the laboratory and in the field; rock-structure interaction; kinematics of structural features at all scales; drilling bit performance optimization; rock core description; rock fall and slope stability analysis; wedge stability analysis.

Modeling: Two- and three-dimensional modeling of rock masses including effect of discontinuities; key-block analysis; numerical simulation technologies; effective stresses and poroelasticity; microfracturing; coupled processes; fracture propagation; development of failure theories; micromechanisms of failure; stability/instability; post-failure brittle analysis; rock bursts.

Mining Engineering: Coal pillar and stope design; subsidence prediction; support of underground mine openings; reduction in pillar size; two-entry systems with yield pillars; bench-and-fill stoping for full recovery; rock reinforcement; wall stabilization with bolts; use of shotcrete and bolts instead of steel and concrete.

Civil Engineering: Tunnel boring machines (TBMs); design and construction of dams, tunnels and underground powerhouses; rock fall analysis and design of remedial measures; design and construction of laterally loaded drilled shafts and partially loaded rock foundations; tunnel stability; rock slope reliability and landslide risk analysis; decision aids for tunneling, behavior of rock socketed piles under axial and lateral loads.

Petroleum (oil and gas) Engineering: Recognition of well-bore breakouts; hydraulic fracturing; prediction of wellbore stability and failure; reservoir development and delineation; drilling and completion practices; reservoir development.

3.4 Shortcomings

Despite the successes, there are still several critical areas of rock mechanics and rock engineering where improvements are needed and for which existing solutions and tools are incomplete and unreliable. More specifically, they include:

General: Prediction of behavior and failure of rock masses with variable properties; scaling of rock mass properties and rock mass mechanisms in both space and time, rock mass failure and *in situ* stresses; development of tools to reliably characterize rock mass structural properties; development of better standards of sampling practice; improvement in drag bits and better understanding of bit-to-rock and cutter-to-rock interaction; development of rapid-use tools to reliably characterize rock mass structural properties; better ways of measuring *in situ* stresses; aging effect on rock excavations; water pressure distribution in joints and pressure relief; prediction of grouting effectiveness; borehole imaging; characterization of layered and anisotropic rock masses; characterization and testing of weak rocks; characterization of coupled phenomena; excavation in difficult, mixed, and rapidly changing rock conditions; excavations in high-stress environments;

water in tunneling; uncertainty and risk-based decisions; too much reliance on rock mass classification systems.

Civil Engineering: Three-dimensional coupled analysis of dam foundations and reservoirs for static and dynamic loading; tunneling in soft ground (soils and weak rocks); effect of rock mass properties on TBM performance; effect of groundwater inflow on tunneling in soft ground.

Mining Engineering: Mining at great depths; prediction and avoidance of rock bursts and coal bumps; mining by remote control.

Petroleum (oil and gas) Engineering: prediction of hydrofrac geometry; borehole stability when drilling through shales and non-consolidated rocks in heavy oil reservoirs; sanding; drill cuttings reinjections; drilling mud/shale interaction; borehole imaging; logging in anisotropic rock masses; borehole stability in shale.

3.5 Partnerships

3.5.1 Background

It is clear that the political and economic climate in which rock mechanics is evolving today is quite different from that of the 1970s and 1980s. Any future collaborative work has to take this observation under consideration.

Industry is operating in a more competitive marketplace where quick returns are expected and benefit margins that were often used for R&D are now limited. R&D is often seen as too costly with limited return. On an average, industry sponsorship of university research funding in the U.S. is only 7% of the total (Clough, 1998). The work environment is also changing with the emergence of high-speed electronic commerce, start-up businesses funded by venture capital, and decentralized computing and communications.

Government has been strongly affected by downsizing and restructuring. Agencies such as the U.S. Bureau of Mines and the U.S. Geological Survey have been eliminated or drastically cut in terms of personnel and funding capabilities. Such agencies have traditionally played a critical role in supporting rock mechanics. Their elimination or downsizing has led to a tightening of funding for research programs. However, the National Science Foundation (NSF) still remains a major source of funding for basic research.

On the academic side, rock mechanics research has become increasingly constrained by reduced government support and short-term objectives by industry. Limited funds exist to support graduate work. Furthermore, fewer graduate students are available as high-paying jobs attract them to industry and away from basic and applied research. The 1990s have also seen the emergence of so-called research universities where expectations of faculty “changed from a focus on teaching undergraduates to one with an emphasis on research, publications, development of graduate courses, and advising of graduate students” (Clough, 1998). The 1990s have also seen a reduction in state funding for higher education from 15-16% in the early 1980s to 9-10% in the mid 1990s (Clough, 1998).

Another element to consider in future collaborative work is the global nature of the problems that society is facing today. Issues of national interest such as waste management, infrastructure development and rehabilitation, construction efficiency and innovation, national security, resource discovery and recovery, mitigation of natural hazards and frontier exploration and development are expected to carry well into the next century. A recent addition has been the emergence of sustainability and the importance of sustainable technologies. Addressing such problems requires engineers with a broad understanding of technical and non-technical (economic, social, ethical, etc.) issues who are “not only technically competent but also are adept at working in teams, flexible in their attitudes about work assignments, adaptable and creative in problem solving, understanding of the global economy, and able to communicate theory ideas to both management, labor and the public” (Clough, 1998). The aforementioned issues are likely to become more critical as population is growing rapidly. In the next two decades, almost 2 billion additional people will populate the Earth, a number equivalent to the world’s total population in 1930. This growth will create demands on an unprecedented scale.

Despite the global nature of today’s problems, rock mechanics and rock engineering has remained divided into disciplines such as mining, civil, and petroleum engineering, geology, and geophysics. These disciplines have traditionally evolved on their own without much cross over between them. They have been very creative in their growth but have come of age and are now stagnating. In chaos theory jargon, they have reached a limiting cycle and are operating at the organizational level more and more on collusion and automatism. Past history has shown that systems that are caught in limiting cycles are at risk.

Despite its many technical contributions to society, rock mechanics has not effectively expanded its markets and publicized its contributions. As a result, rock mechanics does not widely enjoy the privilege of recognition as an independent scientific and engineering discipline, and it is often seen as a low-tech domain. It is poorly known to the general public, to political and economic groups, and to other branches of engineering.

The survival of rock mechanics requires developing collaborative partnerships. It is only through interaction and not individualism or isolationism that rock mechanics will survive and that its full potential can be evoked.

3.5.2 Partnership Benefits

The workshop participants strongly believed that partnerships between academia, industry and government agencies can provide win-win benefits to all parties involved and to society at large. More specifically,

1. Partnerships provide ways of integrating research and education into the real world of design and construction. New technologies can then be integrated into practice more rapidly, thus leading to better and less expensive projects for the industry/government partners. The projects can be better publicized through technical publications by the academic partners.

2. Industry/government partners benefit from faculty and student expertise, access to university laboratory, computing and library resources. Faculty may serve on review panels. Students may help review and evaluate published literature, conduct surveys of professional practice, site visits and data collections and interpretations and conduct tests. In return, university partners benefit from the experience and expertise of industry/government partners with management, marketing, design, installation, and performance monitoring. They also have access to sites for research.

3. Partnerships provide new venues and opportunities for researchers and educators to become more aware of industry's real problems. Academic partners can then keep current with industry practice and become aware of real societal needs where funding is likely to be available.

4. Partnerships allow educators and students to be exposed to real case studies, to gain appreciation for the importance of applying fundamentals to solve practical problems, and ultimately to gain first-hand practical experience through research, sponsorship or internships. As a result, students develop better technical and communication skills, an enhanced learning experience and are better prepared to enter the workforce upon graduation. Further, educators are exposed to real case studies that can be brought into the classroom. Partnerships can also allow educators to spend sabbaticals with companies in industry.

3.5.3 Existing Partnerships

Partnerships are not new and have been found to be successful in the past. The workshop participants gathered several examples of successful partnerships in the field of rock mechanics and rock engineering.

1. The National Institute for Occupational Safety and Health (NIOSH) partnerships have been goal specific and geared toward occupational health and safety issues for the mine workers. The partnerships involve labor. A successful partnership

spanning over 25 years has been between NIOSH and several universities (Univ. of Minnesota, Colorado School of Mines, Virginia Tech.) in the area of boundary element analysis. Another partnership between NIOSH and industry was in the area of reduction of incidence of coal bump injuries through advanced mine design. In general, it appears that partnerships involving NIOSH are done by becoming formal stakeholders or work through stakeholder organizations such as United Mine Workers, Bituminous Coal Operators Association, National Mining Association, and mining universities.

2. The U.S. Department of Energy reported having had several success stories in the last 25 years of partnership between government, industry and academia. For instance, work has been ongoing for developing very deep, high-pressure, overpressure gas resources in western basins. This initiative involved Sandia National Laboratories, Union Pacific Resources and various universities (West Virginia University, University of Wyoming, Colorado School of Mines) in the analysis of results from the wells. Bench-scale tests were conducted by national laboratories and analysis of the data was carried out by universities. DOE's Office of Industrial Technologies has an active partnership program with its Industries of the Future initiative.

3. University of Oklahoma's Rock Mechanics Institute. The institute is funded by NSF and is classified as a State/Industry/University Research Center. It is supported by NSF at 25%, 50% industry and 25% from state agencies. The center involves direct industry participation in research projects and offers strong technology transfer.

4. Potential impact of mining on the verification of the Comprehensive Nuclear Test Ban Treaty. This project was undertaken from 1994 to 1999. It involved industry, government, national laboratories and academia to tackle the problem.

5. Longwall coal mining in Alabama. Fully instrumented longwall shields were tested to measure their performance, and assess the interaction between ground behavior and shield behavior. This project helped developing models to anticipate shield behavior with the ground conditions. It was based on a partnership between Drumond Company, the University of Alabama and the U.S. Bureau of Mines.

6. DOE consortiums with oil and gas industry. The Mexico Tech. excavation consortium is an example of cooperative work on low permeability of tight fractured reservoirs. In that consortium, a company puts up to 50% of the cost and provides data. Students analyze the data and publish theses.

In addition to formal partnerships, there have been promising signs of collaborative work between various disciplines involved in rock mechanics. Most of those collaborations have been spearheaded by the National Academies of Sciences and Engineering. For instance, the recent report on rock fractures (NRC, 1996) involved 11 different national agencies. Another example is the study conducted by the Committee on Advanced Drilling Technologies where drilling is seen as process for breaking and removing rocks to produce boreholes, tunnels and excavations (NRC, 1994). This committee led to the formation of the NADET program, an R&D program for advanced drilling and excavation that was cross-industry including oil and gas, mining, scientific drilling, and other applications of breaking and removing rock. The main idea of the program is to have industry and government provide funds and academia and others conduct the research.

At the professional society level, an example of cooperation is the Underground Technology Research Council which has been created as a joint venture between ASCE and SME. The council deals with underground construction and mining from a broader perspective.

Roth and Roth (2000) reported several examples of successful partnerships in soil mechanics in the following areas: Lateral load behavior of deep foundations susceptible to liquefaction, thermal conditions of sanitary landfills, evaluation of existing metal tensioned systems, and innovative flood protection.

3.5.4 Components of Future Partnerships

Lessons learned from existing and past partnerships can help outline recommendations for future collaboration between research and practice. Below is a list of general ideas proposed by the workshop participants that need to be considered when implementing successful partnerships:

1. The mind set of the partners must be geared toward collaboration rather than separatism. The goals of the partnership, the specific problems to be solved, and the strategies to meet these goals must be clearly identified. Benefits should accrue to all participants.

2. Implementation of a partnership requires a change of mind set from all parties. In particular, the parties must understand the realities of the marketplace and the challenges that each party faces. The economic and political climate might be difficult for some of the parties involved. For instance, it might be difficult for an industrial/government partner to invest in research activity without immediate and direct financial benefit to the company/agency.

3. Partnerships need to focus on execution, on meeting project requirements, and completing the work on time and within budget. They also need to assess their performance and development improvements for future work. Strong networks with clear communication conduits must be identified. Academic partners must realize that industry/government partners require practical and applicable products and solutions.

3.5.5 Potential Partnerships for the Future

Small working groups identified several rock mechanics issues in petroleum, mining and civil engineering that need to be resolved through partnerships.

From the petroleum side, formation characterization was cited as a major issue. There are still many unanswered or partially answered questions with regard to the prediction of rock mass properties, the characterization of fractured reservoirs, *in situ* stresses, and the characterization of weak rock masses. Another issue is technology transfer and how to make sure that rock mechanics is recognized and appreciated by non-rock mechanics personnel. The petroleum working group felt that future progress in rock mechanics is critical for producing cheaper and more hydrocarbons.

The mining engineering discussion group identified two major issues: safety and new mining methods. Safety seems to be a problem, especially for small mining operations in coal and metal mining. Larger operations seem to have been quite successful in keeping mines safe. New methods of mining involve very high extraction ratios underground that make high demands on the ground making safety issues more critical.

The mining working group felt that rock mechanics is critical in mining productivity and in keeping mining companies competitive. However, trying to get mining companies to recognize rock mechanics up front in planning operations and designing mining operations still remains a big challenge. The demise of the U.S. Bureau of Mines has been devastating as far as productivity research is concerned. It was felt that ARMA could play a critical role in building such an awareness in the mining industry.

A critical mining issue that was identified as a definite candidate for partnership is the mitigation of problems due to longwall mining in high-stress environments. This is a national problem that affects the West, the East, the Midwest, stakeholders and other interested parties, DOE, National Mining Association, the state mining associations, the mining companies, the universities (because of their research expertise), the consultants (because of their engineering expertise), organized labor or unorganized labor (because of their safety concerns), equipment companies for the opportunity to develop equipment to respond to the problems, NIOSH for safety issues, and Mining Safety and Health Administration (MSHA) which is the regulatory authority. Such an initiative would bring together safety and productivity and return on investment by maximizing coal recovery. Millions of tons of coal are being lost because of high-stress environments.

The civil engineering participants believed that priority should be placed in the area of education: undergraduate, graduate, and life-long learning. It is clear that a degree is not an education and that engineers today are required to stay up to date with latest changes in technology. Another unresolved important issue is that of uncertainty-based design or problematic-based design in rock engineering practice. Due to the complex nature of rock mechanics, it is necessary to account for rock mass uncertainties in engineering practice. Procedures derived from the fields of probability, statistics, and risk analysis exist to incorporate uncertainties in engineering decision making. However, the use of these procedures is still limited in practice. Another critical issue that is still poorly understood is that of weak rocks such as clay shales.

Other unresolved issues in civil engineering that could be candidates for cooperative work include: improvements and new technology in excavation, excavation in soft ground conditions, use of geophysics to collect more data for rock mass characterization, and characterization of fracture flow. Finally, as for the mining and petroleum industries, there is a need for the civil engineering industry to realize that rock mechanics is indeed valuable in improving the bottom line.

The workshop participants also identified two topics that cut across all disciplines: data and data collection, and technology transfer. There was a strong common opinion among workshop participants that we are overwhelmed by data and that data sharing is rarely done in practice. The rock mechanics profession needs to figure out how to acquire data, assure their quality and make available the data to others in a convenient form. Partnerships between industry/government and universities could help resolve this problem. For instance, industry/government partners could collect the data, and university partners could analyze them.

Another issue dealing with information technology is how can technology transfer take place and be beneficial to all parties. In particular, the goal is to have new cross-cutting technologies that allow for measurements that are less expensive, more reliable and more integrated in practice. In fast-paced information technology, there is a need to keep up with instrumentation advances and visualization tools. It is necessary that the different disciplines of rock mechanics, including academia and practice, come together on this issue.

4. Conclusions and Recommendations

The principal conclusion from the IGU workshop was that the survival of rock mechanics will involve promoting rock mechanics along interdisciplinary lines, exploring new global markets, breaking the traditional internal divisions, and developing collaborative partnerships. Partnerships between industry/government and universities can provide win-win benefits to all parties involved

There was a strong consensus among the workshop participants that ARMA can play a critical role in the future in developing collaborative work in rock mechanics and rock engineering in the U.S. Partnership or consortium development fits well within the overall mission of ARMA. There is a great opportunity for different kinds of multi-disciplinary work.

ARMA can serve as an intermediary between industry, government and academia. It can work with industry to develop goals and help the civil, mining and petroleum industry to achieve their own respective goals. ARMA can also bring awareness to industry. For instance, awareness to mining companies that there are safety improvements and that rock mechanics can play a critical role in increasing safety and productivity, thus improving the bottom line of mining companies. ARMA can also build partnerships in response to industry/government needs. Once the needs are identified, ARMA can help select the most appropriate partners and create task forces.

ARMA is also in a position to facilitate meetings on multi-disciplinary issues by bringing the entire spectrum of industry together around the same table. Several workshop participants mentioned that such initiatives could receive funding from multiple agencies such as NSF, DOE, EPA, MSHA, NIOSH and private companies. State funding through the Experimental Program to Stimulate Competitive Research (EPSCOR) is also available in 19 states where funds are available to match research efforts and industry needs if the topic of interest has been identified by a state for investment.

Finally, ARMA can also serve as a clearinghouse for rock mechanics R&D funded by practice and academia. Such a clearinghouse could be used (1) to catalog past research and work in progress, (2) to document case histories, past failures and problems, (3) to serve as a repository of data that could be shared by academia, (4) to collect shared experiences, and (5) to disseminate results and general information. All these tasks can be done using information technology such as the web.

5. References

Clough, G. W. (1998) The challenges and opportunities that lie ahead in teaching the practice of engineering in the research university, *Inaugural George F. Sowers Lecture*, presented at the Int. Conf. on Site Characterization, Atlanta.

National Research Council (1989) Geotechnology: its impact on economic growth, the environment and national security, Geotechnical Board, Washington D.C., National Academy Press.

National Research Council (1994) Drilling and excavation technologies for the future, Washington D.C., National Academy Press.

National Research Council (1996) Rock fractures and fluid Flow: Contemporary understanding and applications. U.S. National Committee for Rock Mechanics, Washington D.C., National Academy Press.

Roth, M. J. S. and Roth L. H. (2000) Academic-industry partnerships: How can we do more, *Geostrata*, New York, ASCE, April, pp. 26-29.

APPENDIX A

Industry-Government-University Partnership Workshop
June 6, 1999
Vail, Colorado

AGENDA

8:00 a.m. Welcome
Peter Smeallie

8:15 a.m. Agenda Review
Panel Introduction
Visionary/Inspiration
Francois Heuze

8:30 a.m. A) Panel shares success stories (Question 1 of survey)
What has rock mechanics and rock engineering (RMRE) done for your company/clients in past?

B) Panel shares responses to Questions 2 and 3
Unsolved present and anticipated problems

9:30 a.m. Plenary discussion and participant comments

10:00 a.m. Break

10:15 a.m. Selection of one or two representative issues to take into partnership discussion (Divide into small groups; civil, petroleum and mining)

Focus on:

- What is the issue to be addressed?
- What would be the desired goal/outcome?

Criteria to use to select issue(s):

- The issue is national in scope
- Practical and realistic approaches to solutions do exist
- The risk/costs (human, money, etc.) associated with the issue are high

11:00 a.m.	Small groups report in plenary
11:30 a.m.	Lunch Break
1:00 p.m.	Welcome back and summary *Peter/Francois*
1:15 p.m.	Panel shares current/recent partnerships that work Panel shares design ideas
2:15 p.m.	Plenary discussion/participant comments
2:45 p.m.	Break
3:00 p.m.	Working groups develop specific partnership ideas culminating in an action plan

Questions to focus plan include:

- What would the partnership structure look like?
- Who is needed for the partnership?
- Who is not here that should be involved?
- What are the money and other resource needs?
- How will the partnership be evaluated?
- What specific actions will take place to make the partnership a reality?
- Who will commit to taking the actions necessary to make the partnership a reality?

Groups should plan to report back to plenary a proposal for the partnership to solve the issue that includes the following elements:

- Responsible parties
- Scope of work
- Time frames
- Tentative budget
- Likely sponsor

4:00 p.m.	Small groups report partnership proposal back to plenary
4:30 p.m.	Wrap up, report contents, etc.

APPENDIX B

IGU Panelists

Priscilla P. Nelson, Ph.D., Program Director
Geomech, Geotech. & Geo-Environ Systems
Directorate of Engineering
National Science Foundation
4201 Wilson Boulevard, Rm 505
Arlington, VA 22230

Herbert H. Einstein
Professor, Dept. of Civil Engineering, Bldg. 1-342
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

James E. Monsees
Senior Vice President
Parsons Brinckerhoff Quade & Douglas, Inc.
505 South Mail Street, Ste. 900
Orange, CA 92868

Ron Steiger
Hydraulic Fracturing Research Project Leader
Exxon Production Research
P.O. Box 2189
Houston, TX 77252

Jean-Claude Roegiers
MacCasland Chair and Professor
Rock Mechanics Institute
Sarkeys Energy CenterP 119
100 E. Boyd
Norman, OK 73019

Francis S. Kendorski
Vice President
Weir International Mining Consultants, Ltd.
2340 River Road, Ste. 203
Des Plaines, IL 60018

Anthony Iannacchione, PhD, PE
Deputy Director
Pittsburgh Research Laboratory
NIOSH
P.O. Box 18070
Pittsburgh, PA 15236

Toni Grobstein Marêchaux
Office of Industrial Technologies, EE-20
US Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585-0121

Charles Fairhurst
417 5th Avenue, North
South St. Paul, MN 55075

Thomas Mroz
Project Manager, Fuel Resources Division
Federal Energy Technology Center
U.S. Department of Energy
3610 Collins Ferry Road, PO Box 880
Morgantown, WV 26507