Annual Review of U.S. Progress in Rock Mechanics: Rock Mass Characterization (1983)

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Rock Mass Characterization

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PREFACE

In 1981 the U.S. National Committee for Rock Mechanics and its Panel on Rock-Mechanics Research Requirements completed a major technology assessment with publication of the report *Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction*. As a follow-up to this effort, the committee concurred in the suggestion of its then chairman, Neville G.W. Cook, to establish a Panel on Science and Engineering of Rock Mechanics. This new panel was directed to prepare an annual, written assessment of programs and needs in rock mechanics, which, after approval by the committee and the National Research Council, would be published and distributed throughout the rock mechanics community and to program managers and decision-makers in government and industry.

The panel's yearly assessment was to be brief and restricted in scope, and yet emphasize progress applicable to diverse disciplines and problems. The theme selected for the 1982 review is "rock mass characterization, with particular consideration being given to thermomechanical properties determination and in situ stress." Although each annual assessment is intended to be narrow in scope, it is anticipated that the series of reviews will encompass a broad range of rock mechanics themes. The emphasis and organization of these reports are expected to change from year to year, reflecting changes in the priorities of programs and needs in rock mechanics. This first review was conducted under the leadership of Kate H. Hadley, the current chairman of the committee, who has acted as *pro tempore* chairman of the Panel on Science and Engineering of Rock Mechanics.

INTRODUCTION

This report, the first of a series of annual reports intended to review significant progress in selected areas of rock mechanics, focuses on rock mass characterization, with particular consideration being given to thermomechanical properties determination and in situ stress. It reviews events or work completed rather than under way, because documentation for work in progress is often difficult to obtain and, thus, knowledge of investigations or applications in progress may not be as broadly useful as a report of accessible results.

This year's theme was chosen because it cuts across diverse disciplines and problems and builds on the conclusions and reactions to the report *Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction* (U.S. National Committee for Rock Mechanics, 1981). That report demonstrated that, traditionally, the behavior and properties of materials of which, or within which, structures are made have been evaluated principally on the basis of past experience. In general, such experience has not provided an understanding of the causal relationships between the composition and structure of the material and its properties within particular environments.

Increasing numbers of excavations are being made under conditions with which there is little past experience and for which predictive methods of design are necessary to ensure economy and safety. For example, only recently have rock mechanics engineers been prompted to deal with the effects of high temperature because of programs involving geothermal energy exploration and exploitation; in situ recovery of energy from coal, oil shale, and tar sands; tertiary recovery of conventionally reservoired oil using hot steam or water; and nuclear waste disposal. Numerical modeling now provides a powerful basis for prediction as well as for extrapolation of observational models. However, the successful application of numerical models requires a knowledge of the compositional and structural features of the rock mass that affect its behavior and properties. It also requires a knowledge of the appropriate boundary conditions.

FIELD AND IN SITU ROCK MASS CHARACTERIZATION

In practice, only some of the compositional features of a rock mass are determined by field mapping and measurements. Those features that are determined are not necessarily those of the greatest importance to either the behavior of a rock mass or the cost and stability of an excavation. This is the case as much because there is little consensus on what those properties are as because of the difficulty of measurement.

The basic geotechnical description of rock masses suggested recently by the Commission on Classification of Rocks and Rock Masses (1980) of the International Society for Rock Mechanics gives only five properties for each zone. These are the rock name with simplified geological description; the structural characteristics of layer thickness and of fracture intercept; and the mechanical properties of uniaxial compressive strength and of angle of friction of the fractures. As important as these properties are, they are not always sufficient to characterize the rock mass appropriately. Even such detailed mapping studies as were carried out at the Stripa Mine in Sweden as part of a U.S.-Swedish cooperative program (Witherspoon et al., 1980), although useful in defining fracture system geometry, do not give enough information to calculate the flow of water or displacements due to thermal or mechanical loading.

Very extensive and large deformations of the rock mass surrounding full-excavation mining have been measured, providing a model for the behavior of discontinuous rock masses subjected to excavation (Panek and Tesch, 1981). Zones of compressional and extensional strains can be delineated and anticipated in such highly disturbed regions.

Evaluating the suitability of a proposed hard-rock nuclear waste repository requires more information than is customarily obtained by measuring. The Office of Nuclear Waste Isolation (ONWI) of the Battelle Memorial Institute contracted to prepare a manual specifying field and in situ rock mechanics testing procedures in order to standardize rock tests and measurements used in the National Waste Terminal Storage Program (Foundation Sciences, Inc., 1981). In the opinion of ONWI, the data requirements for adequate rock mass characterization include geometry of rock units and disontinuities therein; stress, strength, and deformational properties; and support system performance.

Little is known as yet about the thermomechanical properties of discontinuous rock masses and the effects of thermal cracking on these properties, particularly strength and permeability. In dry rock, the effect of increasing temperature is an irreversible thermal cracking if the rocks are not under some minimum confining pressure; at high temperatures and/or confining pressures, steady state creep is the dominant deformation mechanism (Carter et al., 1981). In wet rock, effects of increasing temperature also include increased pore pressure, enhanced stress-corrosion cracking, and accelerated rock-fluid reactions. Several studies of rapid temperature rise associated with frictional heating along fault zones have indicated that thermally produced increases in pore pressure may substantially reduce resistance to fault motion during earthquakes (Lachenbruch and Sass, 1980; Raleigh and Evernden, 1981). A new and important area of application is the backfilling, support, and sealing of nuclear waste repositories. At the sustained elevated temperatures in this situation, phase changes and hydration/dehydration reactions must be considered in predicting the response of the system.

Over the past three years, thermomechanical investigations have been conducted in crystalline rock at a depth of about 1,100 ft (340 m) at the Stripa Mine. These include full-scale heater experiments. The thermomechanical results obtained thus far show that much more work will be needed to develop a reliable basis for predicting the thermally induced behavior of discontinuous rock masses. The behavior is complex, and the mechanical and hydrological effects of the discontinuities are not yet understood.

Cook (1982) compared measured and calculated values of changes in displacements or temperatures in the rock for six different field experiments in the United States, Sweden, and South Africa. Using linear regression, he showed that when values of the differential stresses are relatively low, linear elasticity—with Young's modulus data from laboratory tests—provides a good predictive model. However, if the values of the mean compressive stresses are small in comparison with those of the differential stresses, the behavior and response of the rock, although systematic, are not linear. Linear heat conduction provides good predictions of changes in rock temperature, but thermal displacements are not predicted well by linear thermoelasticity.

The Los Alamos Hot Dry Rock (HDR) Program is directed toward developing the technology for economical extraction of the geothermal energy contained at accessible depths in the earth's crust, by far the largest energy source available to man (Murphy et al., 1981). To date, the HDR Program has been successful in proving the feasibility of energy recovery and generation of electricity by means of a small research reservoir (Phase I) at Fenton Hill, New Mexico. To develop the technology necessary to create and test a reservoir approaching commercial size, two well bores making up the injection and production legs of the circulating loop were successfully completed last year at depths of 1.9 miles (3 km). Current effort is directed at creating about three fractures connecting the two well bores. Furthermore, thermal-stress cracking research involving fracture toughness and crack growth experiments demonstrated the ease with which a crack or fracture grows under conditions of elevated pressure, temperature, and pore water pressure. This is very important, as a HDR system requires that one or more artificial fractures be produced with up to a 3,300 ft (1 km) diameter in rocks 1.9 to 3.7 miles (3 to 6 km) deep at 570°F (300°C).

The pressing need for large-scale, coupled, thermomechanical and hydraulic test data prompted ONWI to sponsor a 282-ft^3 (8 m^3) block test. The site is located in gneiss in the Colorado School of Mines experimental mine in Idaho Springs (Voegele et al., 1981). It was found that a mineralized joint in gneiss, loaded normally in a 6.6 × 6.6 × 6.6 ft (2 × 2 × 2 m) biaxially loaded block, exhibited a fourfold reduction in permeability when loaded from 0 to 1,000 psi (6.9 MPa) under ambient conditions at 54°F (12°C). A subsequent loading test at 165°F (74°C) to the same stress produced a thirtyfold reduction in permeability. Increasing the temperature alone, with no change in the 1,000 psi (6.9 MPa) normal stress, reduced permeability tenfold. Temperature does not appear to have a positive effect on joint permeability where the joint is unconfined.

An extensive program of thermomechanical in situ tests is under way at the Basalt Waste Isolation Project at Hanford, Washington (Gregory and Kim, 1981; Hocking et al., 1981). Preliminary results from the full-scale heater tests compared favorably with predictions, although measured temperatures and displacements were generally lower than predicted values. The numerical predictive analyses for the heater tests were performed by a linear, two-dimensional, axisymmetric finite-element program. Thermal conductivity was found to be scale independent. An examination of the main heater boreholes with a borescope showed no evidence of rock decrepitation for temperatures up to 536°F (280°C). Stress data are not yet available.

Salt behavior at elevated temperature has been studied mainly in the laboratory. The effect of temperature and pressure on the thermal conductivity and diffusivity of salt was examined by Durham and Abey (1981). The most recent investigations of the thermomechanical properties of salt have been conducted by RE/SPEC, Inc. (Wagner et al., in press) and Sandia National Laboratories (Hansen and Carter, 1980).

ROCK MASS CHARACTERIZATION IN THE LABORATORY

The work cited above reflects a move toward increasingly large-scale and comprehensive field and in situ tests for site characterization. Such tests are costly and limited in scope by the extent to which conditions of stress, pore pressure, and temperature can be altered or controlled, or both. Even field measurements made under ideal conditions are subject to considerable uncertainty; depending on which technique and which data reduction procedure are chosen, significantly different values of modulus or other properties can result (e.g., Bieniawski, 1981). These problems argue for large-scale laboratory tests, in which greater ranges of better controlled environmental conditions can be achieved.

New Testing Facility for Rock Mass Characterization

One large public facility will become available in January 1983, with the opening of the National Geotechnical Centrifuge at the Ames Research Center in Mountain View, California. This centrifuge, the largest in the free world, was modified for geotechnical engineering studies from an existing NASA machine developed for the Apollo space program. When fully developed, it will have the ability to carry 20 tons (18,144 kg) of rock or soil at centrifugal accelerations up to 100 times gravity. This capacity will allow testing of large models to simulated depths of 900 ft (274 m). Accelerations to 300 *g* can be achieved with models weighing up to 3 tons (2,722 kg). Future expansion plans include equipment for earthquake simulation in flight and placement or removal of embankment material in flight.

Centrifuge testing is particularly applicable when body force loading is of concern. Heretofore, most testing has been confined to soils because of limited machine capacity. The capacity of the new machine will allow more rock mechanics testing.

Funding for the development of the National Geotechnical Centrifuge has been provided through a $2.4 million grant from the National Science Foundation (NSF). Development of the facility represents a significant departure from previous NSF procedure in that, for a period of about four years, one fourth of the resources of the NSF geotechnical program was allocated to one project.

The centrifuge will continue under the ownership of NASA. Technical direction is currently being provided by Professor James Cheney, Department of Civil Engineering, University of California at Davis.

Relation of Laboratory Experiments to Prediction of Rock Mass Behavior

Most laboratory testing continues to be done on samples with dimensions of tens to hundreds of millimeters, and much of it is limited to triaxial test configurations. The stresses in triaxial testing are designed to be homogeneous, and the kinematics of the triaxial test allow only limited kinds of near-macroscopic deformation and fracture. However, the ranges of the magnitudes of the minimum and maximum principal stresses, pore fluid pressures, and temperatures that can be achieved and controlled in small triaxial tests are virtually inexhaustible. Therefore, extensive and precise measurements and observations of the behavior and properties of rock specimens under wide ranges of these conditions can be made.

In principle, measurements of the behavior and properties of rock derived from small laboratory tests can be incorporated into numerical models to predict the behavior and properties of rock under conditions more complicated than those of the triaxial test. Numerical models are becoming increasingly sophisticated and lower in cost (e.g., Heuze and Barbour, 1981). Their successful application appears limited not by the codes themselves but by our limited knowledge of the operative failure mechanisms and appropriate geotechnical parameter values for a given practical situation. Repeated comparisons have indicated that field strength values of rock masses are generally several times smaller than laboratory values; field moduli generally fall between 20 and 60 percent of laboratory measured moduli (e.g., Heuze, 1980). This phenomenon has long been attributed to fractures, and scaling laws have been proposed (most recently by Baecher and Einstein, 1981).

Scale change may alter the relative importance of failure mechanisms. What is wanted in order to apply laboratory data to quantitative prediction of rock mass behavior in situ is not merely a size-dependent constitutive relationship with which to scale the data, but the recognition of additional mechanisms not operative under usual laboratory test conditions. Body forces are one clear example; large-scale laboratory testing will likely elucidate others. New field techniques may provide further clues. Increasing use is being made of seismic data to provide insight into the properties of rocks. Measurement of compressional and shear wave velocities and attenuation, combined with bulk density, permits in situ definition of dynamic elastic moduli from which rock mass response under load may be estimated (e.g., Bieniawski, 1980).

IN SITU STRESS DETERMINATION

Of the conditions that require specification for predictive engineering design at depth, the initial state of stress in the rock mass is among the most critical. Of the techniques currently available for in situ stress determination, hydraulic fracturing stress measurement samples the largest volume of rock with a single measurement. It is also one of the more direct methods, in that stresses themselves are measured rather than strains or deformations, which must then be converted into stresses.

In December 1981, a Workshop on Hydraulic Fracturing Stress Measurements was held to assess the current status of the technique and to define areas for future research (Zoback and Haimson, 1982). More than 40 active investigators in the field, representing eight countries, participated. A complete account of the presentations and discussion at the workshop will be available in the published proceedings in April 1983 (U.S. National Committee for Rock Mechanics, in press).

The most exciting aspect of the workshop was the discovery by the various groups of investigators that others were having very similar experiences with the method. The different groups of investigators at the workshop found that they were recording very similar pressure-time data in the field, they were able to interpret them in similar ways, and they were achieving results that were quite encouraging because of several factors. First, the results at various locales were found to be internally quite consistent. Second, the hydrofrac stress measurements generally agreed well with subsurface overcoring stress measurements wherever detailed comparisons could be made, and hydrofrac orientations seemed to agree quite well with other stress measurement methods and stress field indicators (Haimson, 1982; Zoback and Hickman, 1982). Finally, the magnitude of stresses determined by hydraulic fracturing seemed to agree well with stress estimates based on the frictional strength of rock. Nevertheless, it was clear at the workshop that there are a number of areas where the method is more complex than is usually recognized and other areas where further research is required to verify interpretation methods. Needs include the development of a better physical understanding for interpretation of gradual shut-in pressures and secondary breakdown pressures, and an understanding of the variability in tensile strength determination.

CONCLUSIONS

Rock mass characterization for evaluating site response under changing environmental conditions remains limited by a lack of knowledge of both governing mechanisms and appropriate numerical values for large-scale geotechnical properties. Several rock mass characterization schemes are available; they trade off simplicity against completeness.

Significant progress has been made in collecting data on the thermomechanical properties of rock in field tests. However, the causative mechanisms for the observed behaviors require further definition before accurate prediction of rock mass response can be achieved.

A new, large centrifuge facility will be available beginning in early 1983 for scaled experiments in rock mechanics. The extent to which results from this facility and other large-scale laboratory tests can close the cycle of experiment and prediction needed to advance the science of rock mechanics and its application to engineering remains to be explored.

Hydraulic fracturing measurements appear to be reliable indicators of the in situ state of stress.

REFERENCES

Baecher, G.B., and H.H. Einstein. 1981. Size Effect in Rock Testing. *Geophys. Res. Lett. 8*:671-674.

Bieniawski, Z.T. 1980. The 'Petite Sismique' Technique—A Review of Current Developments. pp. 305-318 in *Proceedings, 2nd Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*. Clausthal, Germany: Trans Tech Publications.

Bieniawski, Z.T. 1981. Experience with In Situ Measurement of Rock Deformability. *Geophys. Res. Lett. 8*:675-677.

Carter, N.L., D.A. Anderson, F.D. Hansen, and R.L. Kranz. 1981. Creep and Creep Rupture of Granitic Rocks. pp. 61-82 in *Geophysical Monograph 24*. Washington, D.C.: American Geophysical Union.

Commission on Classification of Rocks and Rock Masses, ISRM. 1980. *Basic Geotechnical Description of Rock Masses* (Document No. 1). Lisbon: International Society for Rock Mechanics. 25 pp. Also in (1981) *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr. 18*:85-110.

Cook, N.G.W. 1982. Questions in Experimental Rock Mechanics. pp. 723-738 in *Issues in Rock Mechanics* (Proceedings, 23rd U.S. Symposium on Rock Mechanics), R.E. Goodman and F.E. Heuze, eds. Littleton, Colo.: Society of Mining Engineers of AIME.

Durham, W.B., and A.E. Abey. 1981. The Effect of Pressure and Temperature on the Thermal Properties of Salt and a Quartz Monzonite. pp. 79-84 in *Rock Mechanics from Research to Application* (Proceedings, 22nd U.S. Symposium on Rock Mechanics), H.H. Einstein, ed. Cambridge: Massachusetts Institute of Technology.

Foundation Sciences, Inc. 1981. *Field and In-Situ Rock Mechanics Testing Manual—Public Draft* (Report ONWI-310). Columbus, Ohio: Office of Nuclear Waste Isolation, Battelle Memorial Institute. 215 pp.

Gregory, E.C., and K. Kim. 1981. Preliminary Results from the Full-Scale Heater Tests at the Near-Surface Test Facility. pp. 137-142 in *Rock Mechanics from Research to Application* (Proceedings, 22nd U.S. Symposium on Rock Mechanics), H.H. Einstein, ed. Cambridge: Massachusetts Institute of Technology.

Haimson, B.C. 1982. Deep Stress Measurements in Three Ohio Quarries and Their Comparison to Near-Surface Tests. pp. 190-202 in *Issues in Rock Mechanics* (Proceedings, 23rd U.S. Symposium on Rock Mechanics), R.E. Goodman and F.E. Heuze, eds. Littleton, Colo.: Society of Mining Engineers of AIME.

Hansen, F.D., and N.L. Carter. 1980. Creep of Rock Salt at Elevated Temperatures. pp. 217-226 in *The State of the Art in Rock Mechanics* (Proceedings, 21st U.S. Symposium on Rock Mechanics), D.A. Summers, ed. Rolla: University of Missouri.

Heuze, F.E. 1980. Scale Effects in the Determination of Rock Mass Strength and Deformability. *Rock Mech. 12*(3-4):167-192.

Heuze, F.E., and T.G. Barbour. 1981. Models for Jointed Rock Structures. pp. 811-824 in *Proceedings, 1st International Conference on Computers in Civil Engineering*. New York, N.Y.: American Society of Civil Engineers.

Hocking, G., J. Williams, P. Boonlualohr, I. Mathews, and G. Mustoe. 1981. Numerical Modeling of the Near Surface Test Facility #1 and #2 Heater Tests. pp. 143-149 in *Rock Mechanics from Research to Application* (Proceedings, 22nd U.S. Symposium on Rock Mechanics), H.H. Einstein, ed. Cambridge: Massachusetts Institute of Technology.

Lachenbruch, A.H. and J.H. Sass. 1980. Frictional Resistance and Heat Flow on the San Andreas Fault. *J. Geophys. Res. 85*:6097-6112.

Murphy, H.D., J.W. Tester, C.O. Grigsby, and R.M. Potter. 1981. Energy Extraction from Fractured Geothermal Reservoirs in Low-Permeability Crystalline Rocks. *J. Geophys. Res. 86*:7145-7158.

Panek, L.A., and W.J. Tesch. 1981. *Monitoring Ground Movements Near Caving Stopes—Methods and Measurements* (Report of Investigation 8585). Pittsburgh, Pa.: Section of Publications, Bureau of Mines. 108 pp.

Raleigh, B., and J. Evernden. 1981. Case for Low Deviatoric Stress in the Lithosphere. pp. 173-186 in *Geophysical Monograph 24*. Washington, D.C.: American Geophysical Union.

U.S. National Committee for Rock Mechanics. 1981. *Rock-Mechanics Research Requirements for Resource Recovery, Construction, and Earthquake-Hazard Reduction*. Washington, D.C.: National Academy Press. 222 pp.

U.S. National Committee for Rock Mechanics. In press. *Hydraulic Fracturing Stress Measurements* (Proceedings of the Workshop, December 1981). Washington, D.C.: National Academy Press.

Voegele, M.D., E. Hardin, D. Lingle, M. Board, and N. Barton. 1981. Site Characterization of Joint Permeability Using the Heated Block Test. pp. 120-127 in *Rock Mechanics from Research to Application* (Proceedings, 22nd U.S. Symposium on Rock Mechanics), H.H. Einstein, ed. Cambridge: Massachusetts Institute of Technology.

Wagner, R.A., M.C. Loken, and H.Y. Tammemagi. In press. Thermomechanical Room Region Analysis of Four Potential Nuclear-Waste Repository Sites in Salt. In *Rock Mechanics for Resource Development, Mining, and Civil Engineering* (Proceedings, 5th Congress of the International Society for Rock Mechanics, April 1983).

Witherspoon, P.A., P. Nelson, T. Doe, R. Thorpe, B. Paulsson, J. Gale, and C. Forster. 1980. Rock Mass Characterization for Storage of Nuclear Waste in Granite. *IEEE Trans. Nucl. Sci. NS-27*(4):1280-1290.

Zoback, M.D., and B.C. Haimson. 1982. Status of the Hydraulic Fracturing Method for In-Situ Stress Measurements. pp. 143-156 in *Issues in Rock Mechanics* (Proceedings, 23rd U.S. Symposium on Rock Mechanics), R.E. Goodman and F.E. Heuze, eds. Littleton, Colo.: Society of Mining Engineers of AIME.

Zoback, M.D., and S. Hickman. 1982. In Situ Study of the Physical Mechanisms Controlling Induced Seismicity at Monticello Reservoir, South Carolina. *J. Geophys. Res. 87*:6959-6974.