ROCK ENGINEERING

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Preface

The chapters of this book follow the rock engineering syllabus taught to fourth-year civil engineering and earth sciences undergraduates at the University of Waterloo in Ontario, Canada. The same students can take supplementary courses relating to surface works and underground construction, or on specialized themes such as laboratory and field testing. Other, more basic courses teach engineering to geologists and geology to engineers.

Having searched for a suitable course text, and finding none that covered the field of rock engineering in a way that would, in our opinion, prepare students adequately for a career in this field, we decided to try to write one ourselves. Our starting point was a compilation of course notes tempered by consulting and research experience. After preparing a first draft on this basis, we filled important gaps and added further depth by extensive referencing of extracts from recent journal publications and conference proceedings. The book is written not only for students, but also, and perhaps mainly, for the practicing civil or mining engineer. It is divided into three parts. The first describes rocks, their environment of water and stress, and how these are explored by drilling, geophysics, mapping, sampling, and index testing. Part 2 explains the various techniques available for design, the behavior of rock, testing for design purposes, and monitoring to check the predictions and assumptions. Part 3 covers field techniques for rock excavation and support.

A planned forthcoming book, *Rock Engineering Applications,* will further demonstrate how these techniques are applied to quarrying and the use of stone, to the design of foundations, slopes, dams, and reservoirs, and to mining and civil engineering works underground.

In many places we have sacrificed detail in favor of a broad and, we hope, balanced picture. Particular attention has been given to recommending supplementary reading wherever detail has been omitted for lack of space.

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Chapter 1

About Rock Engineering

1.1 Historical Perspective

Rock engineering can be traced back to the earliest days of mining and civil engineering. Greek and Egyptian stonemasons worked intricate patterns and constructed columns and interlocking mosaics of rock that for craftsmanship can be scarcely equaled. The pyramid of Cheops in Egypt was constructed 4700 years ago, of more than 2 million blocks of dressed limestone. The first dams were built in Egypt and Iraq around 2900 B.C. Even the earliest of miners faced problems of excavation and rock support on a par with those of present times, equipped with tools and techniques that were much inferior. Early military sappers developed the art of undermining fortifications, and these skills have evolved into present-day tunneling technology.

Recurring disasters throughout the world, notably landslides and rockbursts, kill many and damage much property each year. On average, at least one large dam ruptures each year and two more suffer serious accidents. In Ontario, Canada, alone, rockbursts have occurred at a rate of more than 20 per annum, and a similar number of fatalities from rockbursts have been reported each year in South Africa. All this underscores how little we understand of rock and how poorly equipped we are to control its behavior. Nevertheless, progress has been made. Innovations during the last 100 or so years include the invention of dynamite and AN/FO explosives (1867), electric detonators (1876), tunnel-boring machines (1881), sprayed mortar (1909), rockbolts (1918), shotcrete (1942), tungsten carbide drill bits (1940), the New Austrian Tunneling Method (1950), and oil-hydraulic percussive drills (1971). Reliable instruments are now available to monitor and warn of rock movements at the surface and in underground works. Computation techniques have evolved to the stage where rock conditions can be modeled and predicted with some degree of realism.

1.2 What Is Rock Engineering?

What is meant by *rock engineering,* and how does this differ from *rock mechanics;* what are the differences, if any, between a rock engineer, a geologist, and an engineering geologist?

According to one definition, engineers are people looking for the best available answer today, whereas scientists prefer to wait until tomorrow for the "right" answer. Rock engineers are similarly pressed for time and often have to make decisions based on judgment and experience rather than "truth." More specifically, the rock engineer's responsibility relates to materials of construction, mines, tunnels, foundations, dams, and landslides; in other words, his or her job is to predict and control the behavior of anything made of, in, or on rock.

The labels *rock mechanics* and *geomechanics* are narrowly defined. *Mechanics* is, according to Webster's dictionary, "a...science that deals with energy and forces and their effect on bodies." Certainly, one part of the rock engineer's job is to study the motion, creep, or bursting of rock in a foundation or a mine, but rock engineering is by no means just mechanics. It calls for an appreciation of the nature of geological materials, groundwater, and ground stresses, and the ability to judge conditions and predict how they will affect, and be affected by, construction work. The engineer is called upon not just to study nature passively, but to intervene, excavate, and stabilize, to extract minerals and to create caverns, highways, water reservoirs, and power projects, all the time attempting to preserve and protect the natural environment.

The term *geological engineer* encompasses the *rock engineer* and the *soil engineer,* who both have a different outlook from that of the classical geologist. The classical, or "pure," geologist tries to understand the history (genesis) of rocks, whereas the geological engineer, or engineering geologist, looks to the future, trying to predict the behavior of earth materials as aggregates or fill, and their stability in the walls of excavations. This forward-looking goal of "modeling" the behavior of rock in engineering works is fundamental to applied rock engineering.

Rock physicists (*geophysicists*) use the science of physics to study the behavior of rock materials. One of their tasks is to investigate geologic processes and how rocks behave under high temperatures and pressures deep in the earth's crust, mantle, and core. At great depths, exploration by drilling is very costly, so most of the available information on deep geological structures has come from geophysical exploration, using deep seismic reflection to map layers of differing sonic velocity and therefore density. Deep geological processes can sometimes also be inferred by observing, at surface, rocks that once were deeply buried but now are revealed through processes of tectonics and erosion.

Specialists in these related fields often work together to solve multidisciplinary problems. Many, during a career in geotechnology, apply their knowledge to several fields, and experience in one often conveys benefits in others. Overspecialization is a hazard in a world of complex technology, and a broadly based education can be a greater asset than a very detailed knowledge of one or two highly specialized topics.

1.3 Judgment and Approximation

Rock engineering is more a craft than either an art or a science. Craftsmanship depends on an understanding or "feel" for the materials and a dexterity in manipulating the tools of the trade. Appreciation of materials in this case requires an understanding of basic geology, groundwater, and ground stress regimes and of how these interact. Tools include the methods of site investigation and testing, modeling, computation, design, excavation and stabilization, instrumentation, and monitoring.

To be accomplished in this craft, perhaps the most important attribute is an ability to view a project as a whole and to temper a rigorous scientific method with common sense. In describing the rock engineering work at the Lagrande hydroelectric complex in Quebec, Canada, Murphy and Levay (1985)* remarked that "experienced judgment based on field observations is usually more valid in the assessment of rock treatment requirements than any strictly theoretical approach." Nevertheless, they made good use of mathematical models to dimension the rock pillars and caverns and to investigate rock stresses and seepage gradients around penstocks. The studies were always viewed as of qualitative rather than quantitative significance.

Disasters seem hardly ever to be caused by lack of precision or miscalculation, but much more often by neglect, ignorance, or overspecialization. Mother Nature has a habit of taking advantage of those who turn their backs on her. In geomechanics it pays to be wary, because subsurface conditions can hardly ever be known or predicted accurately in advance of construction. Decisions are made and cost estimates are based on the best information that can be obtained within a limited time and, more importantly, a limited project budget.

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* D.K. Murphy and J. Levay, "Rock Engineering at the Lagrande Complex, Quebec," *Canadian Tunneling* (Tunneling Association of Canada, 1985), pp. 129–141.

Uncertainties are reduced by all available means to a level considered acceptable; but even then, construction often must accommodate the unexpected.

1.4 Rock Engineering and Related Publications

The First International Congress on Rock Mechanics was held in Portugal in 1966, and in 1987 the International Society for Rock Mechanics celebrated its silver jubilee. During those 25 years the body of literature has been expanding at an accelerating pace, with an ever-increasing number of conferences and technical journals devoted to this and closely related themes.

Therefore we have included with this introductory chapter the following brief guide to the literature of rock engineering and related disciplines, including abstract services, books, periodicals, newsletters, and conferences. There must surely be many omissions for which we apologize, but the list may perhaps help those looking for further background reading.

1.4.1 Abstract journals and bibliographies

Engineering Geology Abstracts (quarterly): American Geological Institute, Alexandria, Va.

GEODEX, abstracts relating to geotechnical subjects.

Geomechanics Abstracts, issued and bound with *International Journal of Rock Mechanics and Mining Sciences* (Pergamon, Oxford).

KWIC Index of Rock Mechanics Literature. Part 1 (to 1969), E. Hoek, Ed. (AIME, New York); Part 2 (1969–1976), J. P. Jenkins and E. T. Brown, Eds. (Pergamon, Oxford).

1.4.2 Books

Attewell, P. B., and I. W. Farmer: *Principles of Engineering Geology* (Chapman and Hall, London, 1976).

Bieniawski, Z. T.: *Rock Mechanics Design in Mining and Tunneling* (A. A. Balkema, Rotterdam and Boston, 1984), 272 pp.

Blyth, F. G. H., and M. H. DeFreitas: *A Geology for Engineers,* 6th ed. (Edward Arnold, London, 1974).

Brady, B. H. G., and E. T. Brown: *Rock Mechanics for Underground Mining* (Allen and Unwin, London, 1985), 527 pp.

Brown, E. T., Ed.: *Analytical and Computational Methods in Engineering Rock Mechanics* (Allen and Unwin, London, 1987), 259 pp.

Budavari, S. Ed.: "*Rock Mechanics in Mining Practice,*" Monograph ser. M5, S. Afr. Inst. Mining Mettal., Johannesburg, 282 pp. (1983).

Coates, D. E.: *Rock Mechanics Principles* (Mines Branch Monograph 874, CANMET, Ottawa, Ont., 1970).

Duncan, N.: *Engineering Geology and Rock Mechanics,* 2 vols. (Leonard Hill, London, 1969).

Finkl, C. W., Ed.: *The Encyclopedia of Applied Geology* (Van Nostrand Reinhold, New York, 1984), 644 pp.

Goodman, R. E.: *Methods of Geological Engineering in Discontinuous Rocks* (West Publ., St. Paul, Minn., 1976).
———: *Introduction to Rock Mechanics.* (Wiley, New York, 1980), 478 pp.
Hoek, E., and J. Bray: *Rock Slope Engineering,* 2d ed. (Inst. Min. Metall., London, 1978).
——— and E. T. Brown: *Underground Excavations in Rock.* (Inst. Min. Metall., London, 1980), 527 pp.
Jaeger, C.: *Rock Mechanics and Engineering,* 2d ed. (Cambridge University Press, Cambridge, 1972), 523 pp.
Jaeger, J. C., and N. G. W. Cook: *Fundamentals of Rock Mechanics,* 2d ed. (Chapman and Hall, London, 1979), 593 pp.
Krynine, D., and W. Judd: *Principles of Engineering Geology and Geotechnics* (McGraw-Hill, New York, 1959).
Lama, R. D., V. S. Vutukuri, and S. S. Saluja: *Handbook on Mechanical Properties of Rocks,* 4 vols. (Trans-Tech Publ., Rockport, Mass.). Series on Rock and Soil Mechanics: vol. 1, Vutukuri, Lama, and Saluja, 1974; vols. 2, 3, and 4, Lama and Vutukuri, 1978.
Legget, R. F.: *Geology and Engineering,* 2d ed. (McGraw-Hill, New York, 1962), 884 pp.
McLean, A. C., and C. D. Gribble: *Geology for Civil Engineers,* 2d ed. (Allen and Unwin, Boston, Mass., 1985), 314 pp.
Obert, L., and W. I. Duvall: *Rock Mechanics and the Design of Structures in Rock.* (Wiley, New York, 1967).
Roberts, A.: *Geotechnology* (Pergamon, Oxford, 1976).
Stacey, T. R., and C. H. Page: *Practical Handbok for Underground Rock Mechanics* (Trans-Tech Publ., Rockport, Mass.). Series on Rock and Soil Mechanics, vol. 12, 144 pp. (1986).
Zaruba, Q., and V. Mencl: *Engineering Geology* (Elsevier, New York, 1976).

1.4.3 Periodicals

Bulletin of the Association of Engineering Geologists (Association of Engineering Geologists, Dallas, Tex.).
Bulletin of the International Association of Engineering Geology (Paris, France).
Canadian Geotechnical Journal (Canadian National Research Council, Ottowa, Ont.).
CIM Bulletin (Canadian Institute of Mining and Metallurgy, Montreal, Que.).
Engineering Geology (Elsevier).
Engineering and Mining Journal.
Geotechnique (Institute of Civil Engineers, London).
International Journal of Mining and Geological Engineering (Chapman and Hall, London).
International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts (Pergamon, Oxford).
International Journal of Surface Mining (A. A. Balkema, Rotterdam and Boston).
Journal of the Geotechnical Engineering Division (American Society of Civil Engineers, New York).
Journal of the Soil Mechanics and Foundations Division (continued as *Journal of the Geotechnical Engineering Division,* American Society of Civil Engineers, New York).
Quarterly Journal of Engineering Geology (Scottish Academic Press, Edinburgh).
Rock Mechanics (Springer, Vienna).
Rock Mechanics and Rock Engineering (Springer, Vienna and New York).
Tunnelling and Underground Space Technology (Pergamon, Oxford).

1.4.4 Newsletters

News (International Society for Rock Mechanics; Secretariat: Lisbon, Portugal).
Geotechnical News (BiTech Publishers, Vancouver, B.C.).

1.4.5 Proceedings

Canadian Rock Mechanics Symposia (every 18 months approximately): Sponsored by the Canadian Rock Mechanics Association (CARMA); various publishers.

Congresses of the International Association of Engineering Geologists (every 4 years).

Congresses of the ISRM (every 4 years): 1st—Lisbon (1966); 2d—Belgrade (1970); 3d—Denver (1974); 4th—Montreux (1979); 5th—Melbourne (1983); 6th—Montreal (1987).

International Congresses on Large Dams: Sponsored by the International Commission on Large Dams (ICOLD).

Symposia of ISRM (annual): Various countries and sponsors.

U.S. Symposia on Rock Mechanics (annual): Sponsored by U.S. National Commission on Rock Mechanics; various publishers.

Part

1

Ground Characterization

P1.1 The Four "Elements"

Earth, air, fire, and water, the four elements of the ancients, are replaced in modern geomechanics by soil, rock, water, and stress. Any description or classification of ground conditions has to address each of these four aspects.

The alchemical analogy can be carried further by considering transmutation of the elements. Soils and rocks are quite stable although eventually, in the extensive time frame of geology, soils change to rocks by lithification, and rocks to soils by processes of weathering. Water and stress are much more transient by nature. The water table rises and falls in the fissures and pores of the earth, depending on rainfall and the seasons. A tunnel excavated in saturated ground acts as a drain that removes water, and changes pressures and the directions of flow. Similarly it modifies the stress field, acting as a "stress raiser." Engineering works affect the environment in many ways, and, in turn, the environment governs the behavior of the ground.

P1.2 Characterization—Rock Mass and Rock Material

Each rock formation has a unique "character" that not only bears the imprint of its geological history, but also controls its future behavior in engineering works. Just as a human's character can be estimated in terms of attributes such as height, weight, and intelligence, so a rock can be characterized by a set of properties. Some of these, such as color and grain size, can be observed directly, whereas others, such as strength and durability, can be measured only by testing.

The geologist's traditional role has been to study the history or genesis of rocks, whereas the engineer's has been to predict the performance of these materials in works yet to be constructed. The engineer's observations, tests, descriptions, and classifications, although based on geological groundwork, are substantially different from those of the classical geologist (Deere, 1963; Merritt and Baecher, 1981).

In engineering applications, flaws and weaknesses govern the behavior of the rock and therefore assume a much greater importance than the solid "intact" (unbroken) material. Features such as joints, bedding planes, and surfaces of cleavage or schistosity, cut through the rock (Fig. P1.1). These are usually given the collective name *discontinuities*, although quite often a simpler term, such as joints, fissures, or fractures, is

Figure P1.1 Joints in slate; Les Méchins, Gaspé, Que., Canada.