Introduction to Rock Mechanics

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Preface

Rock mechanics is a truly interdisciplinary subject, with applications in geology and geophysics, mining, petroleum, and civil engineering. It relates to energy recovery and development, construction of transportation, water resources and defense facilities, prediction of earthquakes, and many other activities of greatest importance. This book introduces specific aspects of this subject most immediately applicable to civil engineering. Civil engineering students, at the advanced undergraduate and beginning graduate level, will find here a selection of concepts, techniques, and applications pertaining to the heart of their field—for example, how to evaluate the support pressure required to prevent squeezing of claystone in tunnels, how to evaluate the optimum angle of a rock cut through a jointed rock mass, and how to determine the bearing capacity of a pier socketed into rock. Students in other fields should also find this work useful because the organization is consistently that of a textbook whose primary objective is to provide the background and technique for solving practical problems. Excellent reference books cover the fundamental bases for the subject well. What has been lacking is a relatively short work to explain how the fundamentals of rock mechanics may be applied in practice.

The book is organized into three parts. Part 1, embracing the first six chapters, provides a survey of the methods for describing rock properties. This includes index properties for engineering classification, rock strength and deformability properties, the properties and behavior of joints, and methods of characterizing the state of initial stress. Modern fracture mechanics has been omitted but some attention is given to anisotropy and time dependency. Part 2, consisting of Chapters 7, 8, and 9, discusses specific applications of rock mechanics for surface and underground excavations and foundations. Part 3 is a series of appendices.

One appendix presents derivations of equations, which were omitted from the chapters to highlight usable results. There is also a thorough discussion of stresses in two and three dimensions and instructions in the measurement of strains. Appendix 3 presents a simple scheme for identifying rocks and minerals. It is assumed that the reader has some familiarity with introductory geology; this section distills the terminology of petrology and mineralogy to provide a practical naming scheme sufficient for many purposes in rock mechanics. Part 3 also includes answers to all problems, with elaboration of the methods of solution for a selected set. The problems presented at the ends of each chapter and the worked out solutions in the answers section are a vital part of this book. Most of the problems are not just exercises in filling in values for equations offered in the text, but try to explore new material. I always enjoy learning new material in a practical context and therefore have elected to introduce new ideas in this way.

Although this is largely a presentation of results already published in journals and proceedings, previously unpublished materials are sprinkled through the text, rounding out the subject matter. In almost all such cases, the derivations in the appendix provide complete details.

This book is used for a one-quarter, three-credit course for undergraduates and beginning graduate students at the University of California, Berkeley, Department of Civil Engineering. Attention is riveted to the problems with little time spent on derivations of equations. Appendices 1 and 2 and all materials relating to time dependency are skipped. In a second course, derivations of equations are treated in class and the materials presented here are supplemented with the author's previous book *Methods of Geological Engineering in Discontinuous Rocks* (West Publishing Co.) 1976, as well as with selected references.

I am deeply indebted to Dr. John Bray of Imperial College for illuminating and inspiring contributions from which I have drawn freely. A number of individuals generously loaned photographs and other illustrations. These include K. C. Den Dooven, Ben Kelly, Dr. Wolfgang Wawersik, Professor Tor Brekke, Dr. Dougall MacCreath, Professor Alfonso Alvarez, Dr. Tom Doe, Duncan Wyllie, Professor H. R. Wenk et al., and Professor A. J. Hendron Jr. Many colleagues assisted me in selection of material and criticism of the manuscript. The list includes E. T. Brown, Fred Kulhawy, Tor Brekke, Gregory Korbin, Bezalel Haimson, P. N. Sundaram, William Boyle, K. Jeyapalan, Bernard Amadei, J. David Rogers and Richard Nolting. I am particularly grateful to Professor Kulhawy for acquainting me with much material concerning rock foundations. I am also very appreciative of Cindy Steen's devoted typing.

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Symbols and Notation

Symbols are defined where they are introduced. Vectors are indicated by boldface type, for example **B**, with lower-case boldface letters usually reserved for unit vectors. The summation convention is not used. Matrix notation is used throughout, with ( ) enclosing one and two dimensional arrays. Occasionally, { } are used to enclose a column vector. The notation ***B***(*u*) means that ***B*** is a function of *u*. Dimensions of quantities are sometimes given in brackets, with F = force, L = length, and T = time; for example, the units of stress are given as (FL^{-2}). A dot over a letter or symbol (e.g. $\dot{\sigma}$) usually means differentiation with respect to time. Some of the more commonly used symbols are the following.

$\hat{D}_i$	unit vector parallel to the dip
Δd	change in the length of a diameter of a tunnel or borehole
dev	subscript identifying deviatoric stress components
E	Young's modulus (FL^{-2})
g	acceleration of gravity
G	shear modulus; also, specific gravity
GPa	10^3 MPa
i	angle of the leading edge of an asperity on a joint
I_1, I_2, I_3	invariants of stress
$\hat{I}_{ij}$	unit vector parallel to the line of intersection of planes i and j

k	used for different purposes as defined locally, including permeability (LT^{-1}) and stiffness coefficients
K	used variously for the bulk modulus, the Fisher distribution parameter, permeability (L^2), $\sigma_{\text{horiz}}/\sigma_{\text{vert}}$ and σ_3/σ_1.
l, m, n	direction cosines of a line
ln	natural logarithm
MPa	megapascals (MN/m^2); 1 MPa $\approx$ 145 psi
n, s, t	coordinates perpendicular and parallel to layers (st plane)
n	porosity
N_i	unit vector perpendicular to layers or joints of one set
p, p_w	pressure, water pressure
p_1, p_2	secondary principal stresses
P	force; also, in Chapter 9, a line load (FL^{-1})
q_f	bearing capacity (FL^{-2})
q_u	unconfined compressive strength
RMR	rock mass rating according to the Geomechanics Classification
S	spacing between joints of a given set
S_i	shear strength intercept according to the Mohr Coulomb relationship ("cohesion")
S_j	shear strength intercept for a joint
T_{MR}	magnitude of the flexural tensile strength ("modulus of rupture")
T_0	magnitude of the tensile strength; uniaxial tensile strength unless indicated otherwise
u, v	displacements parallel to x, y; positive in positive direction of coordinate axis
u_r, v_θ	displacements parallel to r, θ
Δu	shear displacement along a joint; also radial deformation
Δv	normal displacement across a joint
V_l, V_t	longitudinal and transverse stress wave velocities in a bar
V_p, V_s	compressive and shear wave velocities in an infinite medium
$\Delta V/V$	volumetric strain
w	water content, dry weight basis
w_L, w_P	liquid limit and plastic limit
W	weight vector
x, y, z	right-handed cartesian coordinates

Z	depth below ground surface
γ	weight per unit volume (FL^{-3})
γ_w	unit weight of water
ε, γ	normal and shear strains
η	viscosity ($FL^{-2}T$)
λ	Lamé's constant; also wavelength
μ	friction coefficient ($= \tan \phi$); also same as η
ν	Poisson's Ratio
ρ	mass density ($FL^{-4}T^2$)
σ	normal stress
$\sigma_1, \sigma_2, \sigma_3$	principal stresses; $\sigma_1 > \sigma_2 > \sigma_3$ (compression positive)
$\sigma_{t,B}$	magnitude of the Brazilian (splitting tension) strength
σ_r, σ_θ	radial and tangential normal stresses
σ'	effective stress
τ	shear stress
τ_p, τ_r	peak and residual shear strength
ϕ	friction angle; variously used as internal and surficial friction angles as defined locally
ϕ_μ	friction angle for sliding on a smooth surface ($i = 0$)
ϕ_j	friction angle for a joint
ψ	angle between the direction of σ_1 and the plane of a joint
$\bar{\omega}$	average displacement of a bearing plate

Contents

1 Introduction

Some knowledge of *rock mechanics* is vital for civil engineers although it is only since about 1960 that rock mechanics has come to be recognized as a discipline worthy of a special course of lectures in an engineering program. That recognition is an inevitable consequence of new engineering activities in rock, including complex underground installations, deep cuts for spillways, and enormous open pit mines. *Rock mechanics* deals with the properties of rock and the special methodology required for design of rock-related components of engineering schemes. Rock, like soil, is sufficiently distinct from other engineering materials that the process of "design" in rock is really special. In dealing with a reinforced concrete structure, for example, the engineer first calculates the external loads to be applied, prescribes the material on the basis of the strength required (exerting control to insure that strength is guaranteed), and accordingly determines the structural geometry. In rock structures, on the other hand, the applied loads are often less significant than the forces deriving from redistribution of initial stresses. Then, since rock structures like underground openings possess many possible failure modes, the determination of material "strength" requires as much judgment as measurement. Finally, the geometry of the structure is at least partly ordained by geological structure and not completely within the designer's freedoms. For these reasons, rock mechanics includes some aspects not considered in other fields of applied mechanics—geological selection of sites rather than control of material properties, measurement of initial stresses, and analysis, through graphics and model studies, of multiple modes of failure. The subject of rock mechanics is therefore closely allied with geology and geological engineering.

1.1 FIELDS OF APPLICATION OF ROCK MECHANICS

Our involvement with rock in the most intimate terms extends backward far into prehistory. Arrowheads, common tools, vessels, fortifications, houses, even tunnels were built of or in rock. Constructions and sculptures, such as the Abu Simbel Temple in Egypt and the pyramids, testify to a refined technique for selecting, quarrying, cutting, and working rocks. In the eighteenth and nineteenth centuries, great tunnels were driven for mine ventilation and drainage, water supply, canals, and rail transport.

In this century the great sculptures on Mount Rushmore (Figure 1.1) demonstrated to the world the enduring resolve of great figures and well-selected granite alike, even while engineers were turning to other materials. In this age, when materials engineers can concoct alloys and plastics to survive bizarre and de-

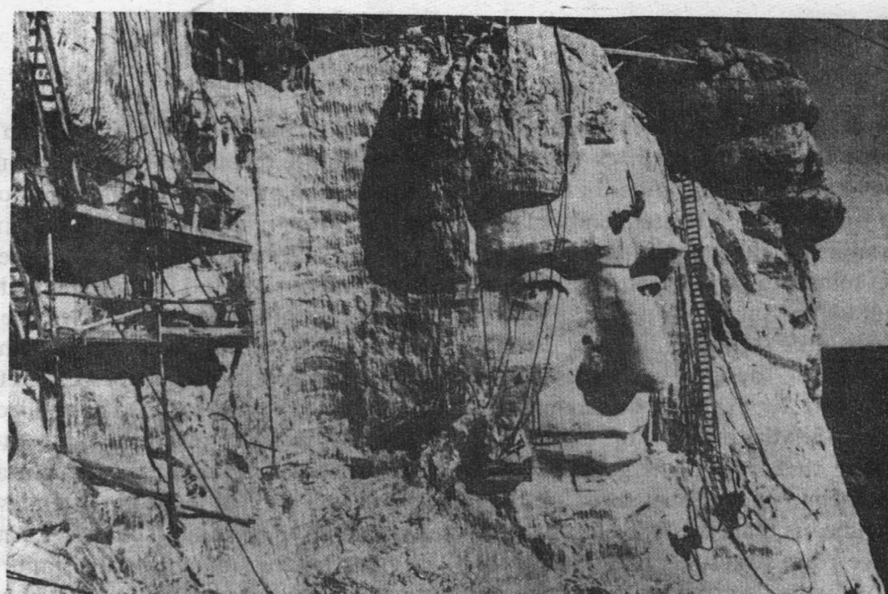

Figure 1.1 Sculpting of Roosevelt and Lincoln in Mount Rushmore. Gutzon Borglum selected the site and adjusted the sculpture to fit its imperfections, even down to the last inch. The weathered rock was removed via controlled blasting with dynamite, the hole spacing and charge becoming progressively finer as the final surface was approached. The last inches were removed by very close drilling and chiseling. [Photo by Charles d'Emery. Reproduced with permission of Lincoln Borglum and K. C. Den Dooven. From *Mount Rushmore, the Story Behind the Scenery*, K. C. Publications (1978).]

manding special requirements, rock work still occupies the energies of industry and the imagination of engineers; for questions concerning the properties and behavior of rock figure prominently in engineering for structures, transportation routes, defense works, and energy supply.

Table 1.1 sketches some of the components of engineering works that involve rock mechanics to a significant degree. Of the many occupations of engineers in planning, design, and construction of works, nine have been singled out in this table because they are often significantly dependent upon rock mechanics input: evaluation of geological hazards in quantitative terms, selection and preparation of rock materials, evaluation of cuttability or drillability of rock and design of cutting and drilling tools, layout and selection of types of structures, analysis of rock deformations, analysis of rock stability, supervision and control of blast procedures, design of support systems, and hydraulic fracturing. These activities are pursued in somewhat different styles according to the nature of the engineering work.

Engineering *structures placed on the surface* of the ground normally do not require study of rock properties and behavior unless the structure is very large, or special, or unless the rock has unusual properties. Of course, the engineer is always on the lookout for geological hazards, such as active faults or landslides that might affect siting. The engineering geologist has the responsibility to discover the hazards; rock mechanics can sometimes help reduce the risk. For example, loose sheets of foliating granite pose a threat to buildings near the feet of cliffs in Rio de Janeiro. The rock engineer may be called upon to design a bolting system, or a remedial controlled blast. In the case of light structures like private homes, the only rock mechanics input would concern testing the potential swellability of shale foundations. However, in the case of very large buildings, bridges, factories, etc., tests may be required to establish the elastic and delayed settlement of the rock under the applied loads. Over karstic limestone, or mined-out coal seams at depth, considerable investigation and specially designed foundations may be required to insure structural stability.

An aspect of engineering for *tall buildings* that involves rock mechanics is control of blasting so that the vibrations do not damage neighboring structures or irritate local residents (Figure 1.2). In cities, foundations of new buildings may lie extremely close to older structures. Also, temporary excavations may require tieback systems to prevent sliding or raveling of rock blocks.

The most challenging surface structures with respect to rock mechanics are large *dams*, especially arch and buttress types that impose high stresses on rock foundations or abutments, simultaneously with the force and action of water. In addition to concern about active faults in the foundation, the hazards of possible landslides into the reservoir have to be carefully evaluated; very fresh is the memory of the Vajont catastrophe, Italy, when a massive slide displaced the water over the high Vajont arch dam and killed more than 2000 people downstream. Rock mechanics is also involved in the choice of materials—rip-rap for protection of embankment slopes against wave erosion, concrete aggregate, various filter

TABLE 1.1 Some Areas of Rock Mechanics Application

Activity Involving a Substantial Rock Mechanics Input

Project	Eval. of Geol. Hazards	Selection of Materials	Eval. of Cuttability, Drillability	Layout and Selection of Types of Works
Surface Structures				
Housing tracts	(2) Landslides, faults			
Bridges, tall buildings, surface power houses	(2) Landslides, faults	(2) Facing stones, concrete aggregate	(1) Drilled shafts for pier foundations	(2) Location of stable site
Dams	(1) Landslides in reservoirs; faults	(1) Rock fill, rip-rap, concrete aggregate		(1) Selection of arch, gravity or embankment
Transportation Routes				
Highways, railways	(1) Landslides	(2) Embankment, base, aggregate, rip-rap		(1) Direction and slope of cuts
Canals, pipelines	(1) Landslides	(2) Embankment, base, aggregate, rip-rap		(1) Direction and slope of cuts
Penstocks	(1) Landslides			(1) Surface penstock vs. lined or unlined tunnel
Surface Excavations for Other Purposes				
Quarries and mine pits	(2) Landslides		(1) Taconite deposits and other hard rocks	(1) Slopes; conveyors; buildings
Spillways	(1) Landslides			(2) Side hill vs. tunnel; slopes

(1) Very relevant.
(2) Somewhat relevant.

Analysis of Deformations	Analysis of Stability	Supervision of Blasting	Design of Support System	Hydraulic Fracturing
(2) Rebound in shales				
(2) Reactions for pretensioning; subsidence engineering	(2) If on cliff edge or over old mines	(1) Control near existing building	(1) Tiebacks in temporary excav.	
(1) Vertical and horizontal	(1) Abutment, foundation	(1) Abutment galleries cutoff trench, quarry	(1) Abutments; found.; reservoir slopes	Potential use for cutoffs
(2) Shale rebound; steep urban cuts	(1) Cut slopes	(1) Perimeter control	(2) Steep cuts in cities	
(2) Shale rebound; steep, urban cuts	(1) Cut slopes	(1) Perimeter control	(2) Steep cuts in cities	
(1) For tunnel penstocks				
(2) To support monitoring programs	(1) Rock slopes	(1) Protection of struct. in and near pit	(2) Protection of struct., portals	
(2) To support monitoring programs	(1) Rock slopes	(1) Protection of struct. in and near cut	(2) For tunnel spillway	

TABLE 1.1 *(continued)*

Activity Involving a Substantial Rock Mechanics Input

Project	Eval. of Geol. Hazards	Selection of Materials	Eval. of Cuttability, Drillability	Layout and Selection of Types of Works
Dry Underground Excavations				
Caving mines	(1) Faults; air blasts	(2) Yielding supports	(1) Selection of long-wall cutters; moles	(1) Entire layout
Stable mines	(1) Faults; rock bursts		(1) Selection of mining tools	(1) Selection of mining scheme
Tunnels	(1) Faults; rock bursts		(1) Design of mole cutters	(1) Shape, size
Underground chambers	(1) Faults; rock bursts		(2) Bidding excavation costs	(1) Orientation
Defense works	(1) Faults; rock bursts			(1) Choice of depth
Energy Development				
Petroleum	(2) Faults; rock bursts		(1) Improving rates	
Geothermal	(2) Faults; rock bursts		(1) High temperature and salinity effects	
Nuclear power plants	(1) Faults; landslides	(2) Concrete aggregate		(2) Water-tight core
Nuclear waste disposal	(1) Faults	(1) Best rock choice for waste isolation		(1) Retrievability, stability
Energy storage caverns for oil, water, air, LNG	(1) Faults	(2) Special linings		(1) Leakproof curtain
Solution Mining				

(1) Very relevant.

(2) Somewhat relevant.

Analysis of Deformations	Analysis of Stability	Supervision of Blasting	Design of Support System	Hydraulic Fracturing
(1) To support monitoring programs	(1) Airblast avoidance; ore dilution anal.	(1) Avoid premature detonation	(1) Haulageways	(2) Solution mining
(1) To support monitoring programs	(1) Access tunnels, stopes, etc.	(1) Control of perimeter; vibration	(1) Rock bolts, shotcrete	
(1) To support monitoring programs	(1) Roof, wall, invert.	(1) Control of perimeter; vibration	(1) Select. temp. and perm. supports	
(1) Support monitoring; design of details	(1) Roof; pillars; invert.	(1) Control of perimeter; vibration	(1) Rock bolts or shotcrete	
(1) Support monitoring; design of details	(1) Under blast loads	(1) Control of perimeter; vibration	(1) Rock bolts or shotcrete	
	(1) Deep holes in shale, evaporites depth of casing			(1) To improve permeability
	(1) Depth of casing			(1) Development of dry hot rock
(2) Rock slope monitoring	(1) Rock slopes; waste disposal		(1) Rock slopes and core shaft	
(1) Support of monitoring	(1) Effect of +200°C	(1) Control of perimeter; vibration	(1) Backfill for canisters	(1) Intermediate level storage
(1) Design and monitoring	(1) Effect of + or −200°C	(1) Control of perimeter; vibration	(1) Long design life	
(1) Monitoring surface subsidence	(1) Surface subsidence			(1) New technique