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ABSTRACT

The results of a survey, conducted by the Committee on Rock Mechanics, to determine the status of training and research in rock mechanics in presented in this publication. In 1964 and 1965 information was gathered by questionnaires sent to industries, selected federal agencies, and universities in both the United States and Canada. Results are summarized for each of these three sources of information. The ten appendices include the following lists: previous conferences on rock mechanics; the 244 responding universities with course information; publications used for teaching rock mechanics; theses in rock mechanics through 1965; university theses and government projects categorized by scope; companies responding to questionnaires; government research projects; and research needs in rock mechanics applied to highways. Sample questionnaires are included. (PR)

Rock-Mechanics Research

NATIONAL ACADEMY OF SCIENCES NATIONAL RESEARCH COUNCIL

Rock-Mechanics Research

A SURVEY OF UNITED STATES RESEARCH TO 1965,
WITH A PARTIAL SURVEY OF CANADIAN UNIVERSITIES

COMMITTEE ON ROCK MECHANICS
DIVISION OF EARTH SCIENCES
DIVISION OF ENGINEERING
NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

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Preface

The need for a better understanding of the physical - mechanical properties of rock and of how stresses in the earth's crust affect those properties becomes ever more apparent with the unprecedented increase in major civil engineering construction now under way. The structural integrity of large buildings, dams, bridges, and many other forms of construction is vitally dependent upon the behavior under stress of the rocks that constitute their foundations. Knowledge of rock mechanics, rock stresses, and geologic structures is also essential to mining, petroleum engineering, and various other industrial activities. Rock mechanics is of special interest to scientists concerned with the fundamental nature of the materials making up the earth's crust.

To determine the current status of research and of technical training in the United States, to point out strengths and deficiencies, and to make recommendations to guide future development, in 1963 the President of the National Academy of Sciences appointed the Committee on Rock Mechanics.[1]

At that time there was neither agreement on the scope of rock mechanics nor a generally accepted definition of it. Therefore, to serve as a basis for both defining the field and evaluating

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[1] This was the second NAS committee to deal with rock mechanics; from 1945 until 1949, the Committee on Experimental Deformation of Rocks, under the chairmanship of Dr. Eleanora B. Knopf, formulated and coordinated a program for systematic research on the mechanisms of rock deformation and assisted in establishing and fostering research on rock deformation in various laboratories in the United States.

The Highway Research Board (NRC Division of Engineering) has an active Committee on Soil and Rock Properties (SGF-C2) that has just completed a list of research needs in the area of rock mechanics. The list will soon be published as a part of a highway research circular (Appendix J).

its current state, the Committee undertook a survey of research and education in rock mechanics in the United States.

Because this was to be the first such survey the Committee hoped for a comprehensive response. Although it did not reach all individuals and organizations with a direct interest in rock mechanics, the results of the survey are deemed to be of value in achieving its aims. In addition, the Committee hopes that publication of this report may elicit responses from some of those who were not reached by the survey. The Committee thanks those who provided information for this survey and asks them to report any significant changes in their rock-mechanics programs. Within three to five years from the date of this report, the Committee expects to survey the field again.

The Committee expresses its appreciation to the 53 companies listed in Appendix H; the Office of Aerospace Research, U.S. Air Force; the Office of the Chief of Research and Development, U.S. Army; the Division of Research, U.S. Atomic Energy Commission; the Bureau of Reclamation, U.S. Department of the Interior; and the National Science Foundation, for financial support of the Committee's activities, including preparation of this report.

August 1966

William R. Judd
Chairman

Contents

Introduction

The inability of engineers and scientists to predict the behavior of rock under the stresses imposed by man's excavations and structures, particularly the large loads of major civil engineering works, has been emphasized dramatically in recent years by several major disasters caused by rock failure. Perhaps equally as important as man's lack of knowledge in such problems is the frequent failure of designers and builders to obtain and use knowledge and skills that may be available from allied disciplines.

The collapse of the Malpasset Dam in Southern France in December 1959, resulting in the loss of some 450 lives, illustrates these deficiencies vividly. The engineering report after the disaster attributed the probable causes to the presence of a fault in the bedrock in which the foundation of the 200-foot-high concrete-arch dam was laid and to the poor local mechanical strength of the gneissic bedrock. Had these factors been properly evaluated before construction, the disaster might have been avoided.

An even more catastrophic example of this problem occurred some four years later. On October 9, 1963, a wave estimated to be 300 ft high, swept over the crest of Italy's 858-foot-high Vaiont Dam and rushed down the Piave Valley, obliterating the city of Longarone and taking approximately 2,500 human lives. This destructive wave was generated when 325 million cubic yards of rock and debris from the reservoir wall suddenly slid into the reservoir, displacing a major portion of the impounded water over the top of the dam. The dam itself received no major damage and retained its structural integrity. All too often, a cause of such disasters may lie in the failure of the builders to make a careful enough study of the composition, behavioral characteristics, and geologic structure of the surrounding bedrock.

Other kinds of man's works are subject to similar failures for similar reasons. The collapse of a shaft-roof in a mine near

Coalbrook, South Africa, in 1960, took the lives of 435 trapped miners and caused abandonment of the mine; later in the same year a rockfall in a gold mine under the streets of Johannesburg killed 15 miners; in a Paris suburb, in June 1961, the roofs of several natural caverns collapsed under the weight of some 50 houses, apartments, and a factory, taking at least 20 lives; in 1964, a landslide covered a sulfur mine in Taiwan, trapping 25 miners.

This same lack of knowledge about rock behavior may also have serious economic, though not necessarily catastrophic, effects. Large quantities of oil remain in reservoir rock because the theory and extraction techniques that will permit greater recovery are lacking. An engineering structure may be over-designed if based upon safety factors that are intuitively rather than quantitatively derived. For example, a tunnel carrying water under high head may have enough concrete and reinforcing steel in the lining so that little if any stress from the water pressure is transferred to the rock surrounding the lining. This inefficient use of material results from the lack of a generally acceptable theory that will evaluate precisely the percentage of the stress that can be borne satisfactorily by the rock. In mining, it is common to leave very large rock pillars unmined so that they can support the roof of a stope; if, however, the theory and instrumentation are available to evaluate accurately the strength of the rock in roof and pillars, a large percentage of the ore in the pillars might be recovered safely.

The foregoing examples were selected to emphasize that a major goal of rock mechanics must be to develop procedures that will permit accurate evaluation of the physical properties of rock so that scientists and engineers can make quantitative predictions on how these properties will respond to changing forces, both natural and man-made. Significant progress toward the achievement of this goal requires a nationwide effort.

It is clear also that this effort must be interdisciplinary in scope because scientists and engineers working in diverse fields are concerned with problems in which rock mechanics is an important factor. Mining engineers, for example, use rock mechanics in designing stable openings for shafts and drifts. Civil engineers use rock mechanics to determine the stability of steep rock cuts for highways. Blasting experts use rock mechanics to understand exactly how rock breaks. Petroleum engineers use rock mechanics in the development of more-efficient designs for drilling bits. Structural geologists and tectonophysicists use rock mechanics to explain the mechanisms of folding and faulting of the rock formations of the earth's crust.

To provide a national focus for research and training in rock mechanics, the National Academy of Sciences in 1963 established the Committee on Rock Mechanics. Its members were selected from all fields concerned with significant aspects of the subject: geology, physics, and geophysics; and civil, mechanical, mining, and petroleum engineering. The Academy charged the Committee with the following tasks:

1. Define the field of rock mechanics
2. Encourage and improve among scientists and engineers the communication and dissemination of literature concerning rock mechanics
3. Determine the present status of professional and academic training in rock mechanics in American universities
4. Survey current research in rock mechanics in government, industry, and universities, in order to identify possible gaps in such research
5. Serve as a national focus for rock mechanics

As a first step, the Committee agreed upon and recommends for general use the following definition of the field:

> Rock mechanics is the theoretical and applied science of the mechanical behavior of rock; it is that branch of mechanics concerned with the response of rock to the force fields of its physical environment.

In approaching its second task, the Committee noted that the first symposium devoted wholly to the subject of "rock mechanics" was held in 1956 at the Colorado School of Mines. Since that time, at least 25 United States and 25 international conferences and symposia have dealt entirely or significantly with rock mechanics. (Appendix A lists conferences through 1965 for which proceedings have been or will be published.) Along with a recent increase in the number of meetings concerned entirely with rock mechanics, the number of sessions devoted to this subject at the annual meetings of professional societies has also increased. This growth in interest led the Committee to sponsor several meetings of representatives of those professional societies known to be significantly concerned with rock mechanics. The goal of these meetings was to form a permanent group to coordinate national and regional symposia and to sponsor an annual interdisciplinary symposium. Accordingly, on November 1, 1965, the Intersociety Committee for Rock Mechanics was established.*

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*The following societies are represented on the Intersociety Committee: (1) American Geophysical Union–Section on Tectonophysics. (2) American Institute of Mining, Metallurgical, and Petroleum Engineers–Committee on Rock Mechanics. (3) Society of Mining Engineers–unit committees on rock mechanics, in the Coal Division and in the Mining and Exploration Division. (4) Society of Petroleum Engineers. (5) American Society for Testing and Materials–Subcommittee 12, on Rock Mechanics, of Committee D-18. (6) American Society of Civil Engineers–Committee on Rock Mechanics. (7) Geological Society of America–Committee on Rock Mechanics in the Engineering Geology Division. (8) Association of Engineering Geologists. (9) Highway Research Board–Committee on Soil and Rock Properties. (10) Seismological Society of America. (11) Society of Exploration Geophysicists.

As one of its first actions, the Intersociety Committee agreed to "promote an annual, truly interdisciplinary conference on rock mechanics."

In 1964 and 1965, the Committee undertook its third and fourth tasks, determination of the status of training and of research in rock mechanics, by means of a survey. The portion of the survey concerned with academic training was broadened to include Canadian as well as United States universities. Questionnaires were sent to industries, universities, and federal agencies believed to be involved directly in research in rock mechanics or in practical application of its principles. Answers confirmed the belief that rock mechanics is part of many disciplines. Current research in rock mechanics includes:

1. Petrofabric study of rock thin-sections to determine how a rock will react under load

2. Prediction of whether crushing of fill-rock will occur in a high, rock-fill dam

3. Determination of the displacement of large openings in rock when they are acted upon by the shock wave from a nuclear explosion

4. Development of new methods for rapid excavation of tunnels

5. Development of a design for nuclear devices and of procedures and principles for site selection and emplacement that will permit their safe and economical use for excavation of deep canals

6. Development of methods and instruments to determine accurately the effects of mining operations upon the static stress around a mine opening

7. Development of analytical methods for design of the steep rock slopes that are necessary for maximum ore recovery in open-pit mines

8. Development of theories and experiments to explain why and how rock fails when it is subjected to such forces as thermal energy, impact loads, electrical arcs, and water-wave action

As a framework for analyzing the survey results, the Committee prepared an outline of types of research being conducted in rock mechanics, separated into three main categories:

1. Fundamentals (Theory and model studies)
   a. State of stress in the earth's crust
   b. Stress-and-strain distribution
   c. Failure theory
   d. Stress-wave theory

2. Measurements
   a. Laboratory: (1) static, (2) dynamic
   b. Field: (1) static, (2) dynamic

3. Applications 5
    a. Surface foundations, surface excavations, and natural slopes
    b. Underground openings (including boreholes)
    c. Rock as a construction material
    d. Comminution: (1) drilling, (2) blasting, (3) crushing
    e. Subsidence
    f. Structural geology

Academic Education and Research

The status of academic research and training in rock mechanics in the United States and Canada can be evaluated from the responses to questionnaires (Appendixes B and C) sent in March 1964 to 477 departments in 303 universities and colleges. Replies were received from 344 departments (72 percent) in 244 universities (80 percent). These replies, based on the areas of concern of the responding departments, have been grouped in four major categories: (1) civil engineering, (2) geology and geophysics, (3) mining engineering, and (4) petroleum engineering.

EDUCATION

The survey shows that partial or complete courses in rock mechanics are offered by 188 departments (55 percent). Only 53 departments (15 percent), however, at 47 universities (19 percent), provide complete courses at either the graduate or the undergraduate level (Tables 1 and 2): mining engineering, 31; geology and geophysics, 16; civil engineering, 4; and petroleum engineering, 2.

Table 1

Number of Courses in Rock Mechanics

Department	Courses[a]			
	Undergraduate		Graduate	
	Partial	Complete	Partial	Complete
Civil Engineering	34	0	8	4
Geology and Geophysics	102	6	35	14
Mining Engineering	24	28	9	22
Petroleum Engineering	2	0	2	4

[a] Data represent actual number of courses taught but do not indicate total number of individual departments offering such courses.

Table 2

Complete Course in Rock Mechanics

	Institution			
Department	Undergraduate	Total	Graduate	Total
Civil Engineering	—		Illinois, U. of	
	—		Laval U.	
	—		McMaster U.	
	—		Notre Dame, U. of[a]	4
Geology and Geophysics	Arizona, U. of		Arizona, U. of	
	Boston C.		Boston C.	
	—		California Inst. of Tech.	
	California, U. of (L.A.)		California, U. of (L.A.)	
	—		Columbia U.	
	—		Cornell U.[a]	
	—		Florida State U.	
	Lawrence C.		—	
	—		Massachusetts Inst. of Tech.	
	—		Massachusetts, U. of	
	McGill U.		McGill U.	
	—		Michigan State U.	
	Michigan Tech. U.		—	
	—		North Carolina, U. of	
	—		Stanford U.	
	—	6	Washington, U. of	14
Mining Engineering	Alabama, U. of		Alabama, U. of	
	Alaska, U. of		—	
	Alberta, U. of		—	
	Arizona, U. of		Arizona, U. of	
	California, U. of (Berkeley)		California, U. of (Berkeley)	
	Colorado Sch. of Mines		Colorado Sch. of Mines	
	Columbia U.		Columbia U.	
	École Polytechnique		—	
	Idaho, U. of		Idaho, U. of	
	Illinois, U. of		Illinois, U. of	
	Kentucky, U. of		Kentucky, U. of	
	McGill U.		McGill U.	
	Michigan Tech. U.		Michigan Tech. U.	
	Minnesota, U. of		Minnesota, U. of	
	Missouri, U. of (Rolla)		Missouri, U. of (Rolla)	
	Montana Sch. of Mines		Montana Sch. of Mines	
	New Mexico Inst. of Mines and Tech.		—	
	—		Nova Scotia Tech. C.	
	Ohio State U.		—	
	Pennsylvania State U.		Pennsylvania State U.	
	Queens U.		Queens U.	
	Saskatchewan, U. of		—	
	South Dakota Sch. of Mines		—	
	Texas Western C.[b]		—	
	Toronto, U. of		Toronto, U. of	
	—		Utah, U. of	
	Virginia Polytechnic Inst.		Virginia Polytechnic Inst.	
	Washington State U.		Washington State U.	
	Washington, U. of		Washington, U. of	
	—		Wisconsin, U. of	
	Wisconsin State C. and Inst. of Tech.	28	—	22
Petroleum Engineering	—		Louisiana State U.	
	—		Texas, U. of	2

[a] Being planned.
[b] Being dropped.

Table 3

Number of Graduate Research Assistants Working in Rock Mechanics During 1964

Civil Engineering	Number of Assistants	Mining Engineering	Number of Assistants
Illinois, U. of	17	Pennsylvania State U.[a]	10
Michigan State U.	4	Colorado Sch. of Mines	9
Maryland, U. of	3	McGill U.[b]	9
North Carolina State U.	2	Missouri, U. of (Rolla)	7
Washington, U. of	2	Minnesota, U. of[c]	5
Alberta, U. of	1	California, U. of (Berkeley)[d]	5
Georgia Inst. of Tech.	1	South Dakota Sch. of Mines and Tech.	4
Utah, U. of	1	Arizona, U. of	2
Worcester Polytechnic Inst.	1	Columbia U.	2
	32	Illinois, U. of[e]	2
Geology and Geophysics		Saskatchewan, U. of	2
South Dakota School of Mines and Tech.	5	Utah, U. of	2
Texas A&M U.	5	Wisconsin, U. of (Madison)	2
Columbia U.	4	Alberta, U. of	1
Massachusetts Inst. of Tech.	3	Michigan Tech. U.	1
California, U. of (L.A.)	2	New Mexico Inst. of Mines and Tech.	1
Dartmouth C.	2	Ohio State U.	1
Boston C.	1	Queens U.	1
Illinois, U. of	1	Toronto U.	1
Ohio State U.	1		67
	24	Petroleum Engineering	
		Texas, U. of	7

[a] Department of Mineral Industries.

[b] Department of Mining Engineering and Applied Geophysics.

[c] Department of Mineral Engineering.

[d] Department of Mineral Technology.

[e] Department of Mining, Metallurgy, and Petroleum Engineering.

The survey also revealed that, of the 64 publications used for teaching courses in rock mechanics (Appendix D), 13 are textbooks in general use, i.e., each is used by more than five departments. The over-all scope of these 64 books is very broad, including but not restricted to such widely differing subjects as electronic devices, engineering geology, elasticity, matrix analysis, and mining. Thus, there is only slight concurrence on what is meant by rock mechanics, and there is a clear need for a textbook that spans the broad principles of theoretical rock mechanics as well as the interdisciplinary aspects of experimentation and applications in this field. The Committee believes that part of this need will be met by two recently published texts.[1,2]

Graduate Students

The present strength of research and training in rock mechanics, when compared with previous years, is indicated by the relatively large number of graduate students (163) who conducted research during the academic year 1963-1964. Of these, 130 were supported by research assistantships. Departments of mining engineering have the greatest number of assistants working in rock mechanics—67 compared with 63 for all the other departments combined (Table 3 and Figure 1). The Department of Civil Engineering at the University of Illinois has more assistants—17—than any other department; next in order are in the mining departments—10 at Pennsylvania State University, 9 at Colorado School of Mines, and 9 at McGill University.

Financial support for graduate assistants is obtained from diverse sources. Approximately two thirds of all such support is provided by the American Petroleum Institute, the National Science Foundation, and the U.S. Air Force. The remaining support is obtained from other federal agencies, universities, research organizations, state governments, and industry. Another type of support that does not appear in the survey includes the aid and experience provided to students through employment on rock-mechanics projects, both during the school year and during the summer; the Bureau of Mines and the Corps of Engineers, in particular, provide this kind of support.

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[1] Coates, D., Rock Mechanics Principles, Mines Branch Monograph 874, Department of Mines and Technology Survey, Ottawa (1965).

[2] Duvall, W. I., and L. Obert, Rock Mechanics and the Design of Structures in Rock, Wiley, New York (in press).

Table 4

Master's and Doctoral Theses in Rock Mechanics in United States and Canada (from Appendix E)

Institution	M.S. Degree				Ph.D. Degree				Total
	Civil Eng.	Geology and Geophysics	Mining Eng.	Petroleum Eng.	Civil Eng.	Geology and Geophysics	Mining Eng.	Petroleum Eng.	
Alberta, U. of	–	1	–	–	–	–	–	–	1
California, U. of (Berkeley)	–	–	1[a]	9[a]	–	–	1[a]	1[a]	12
California, U. of (L.A.)	–	2	–	–	–	3	–	–	5
Colorado Sch. of Mines	–	–	20	–	–	–	3	–	23
Columbia U.	–	3	13	–	–	1	1	–	18
Georgia Inst. of Tech.	–	–	–	–	2	–	–	–	2
Harvard U.	–	–	–	–	–	4[b]	–	–	4
Illinois, U. of	1	1	5[c]	–	8	1	7[c]	–	23
Massachusetts Inst. of Tech.	–	–	–	–	–	1	–	–	1
McGill U.	–	–	16[d]	–	–	–	3[d]	–	19
Michigan State U.	1	–	–	–	4	1	–	–	6
Michigan Tech. U.	–	–	2	–	–	–	–	–	2
Minnesota, U. of	–	–	7[e]	–	–	–	2[e]	–	9
Missouri, U. of (Rolla)	–	–	14	–	–	–	1	–	15
Montana Sch. of Mines	–	–	2	–	–	–	–	–	2
Ohio State U.	6	–	–	–	–	1	–	–	7
Pennsylvania State U.	–	–	7	–	–	–	3	–	10
Queens U.	–	–	7	–	–	–	2	–	9
S. Dakota Sch. of Mines & Tech.	–	–	5	–	–	–	–	–	5
Southern California, U. of	–	1	–	–	–	–	–	–	1
Stanford U.	–	1	–	–	–	3	–	–	4
Texas, U. of	–	–	–	11	2	2	–	3	18
Utah, U. of	7	–	–	–	1	–	–	–	8
Virginia Polytechnic Inst.	–	–	7	–	–	–	–	–	7
Wisconsin, U. of	–	–	2	–	–	–	2	–	4
Total	15	9	108	20	17	17	25	4	215

[a] Department of Mineral Technology.
[b] Department of Geological Sciences.
[c] Department of Mining, Metallurgy, and Petroleum Engineering.
[d] Department of Mining Engineering and Applied Geophysics.
[e] Department of Mineral Engineering.

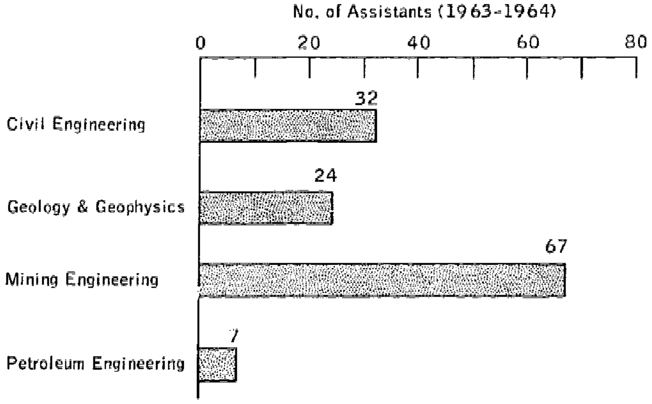

Figure 1
Number of graduate assistants conducting rock-mechanics research.

Theses

The distribution, by institution, of 215 master's theses and doctoral dissertations in rock mechanics produced in the interval 1930 to 1964 was regarded by the Committee as an indication of the distribution of rock mechanics research in the universities (Table 4 and Appendix E).* The result generally resembles that obtained with numbers of graduate assistants as the indicators.

The growth of rock-mechanics research over the past 15 years, as indicated by thesis production, is shown in Figure 2. Mining engineering departments were the early leaders in training and research and began sponsoring master's theses in this field about 1930—approximately 20 years earlier than other departments. Although the total number of master's degrees in rock mechanics granted by departments of geology, petroleum engineering, and civil engineering is small, there has been moderate growth since 1959. The comparative numbers of theses written at the various universities have changed considerably over the past three decades; as shown in Figure 3, the universities that led in the production of master's theses before 1960 have not retained their position.

Before 1960, few doctoral theses in rock mechanics were produced; however, as shown in Figure 2, the number of such theses has increased sharply since then, and it continues to increase. Through 1962, departments of mining engineering

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*Table 4 and Appendix E were compiled solely from an examination of thesis titles. Some rock-mechanics theses without clearly definitive titles may therefore have inadvertently been omitted or erroneously categorized.

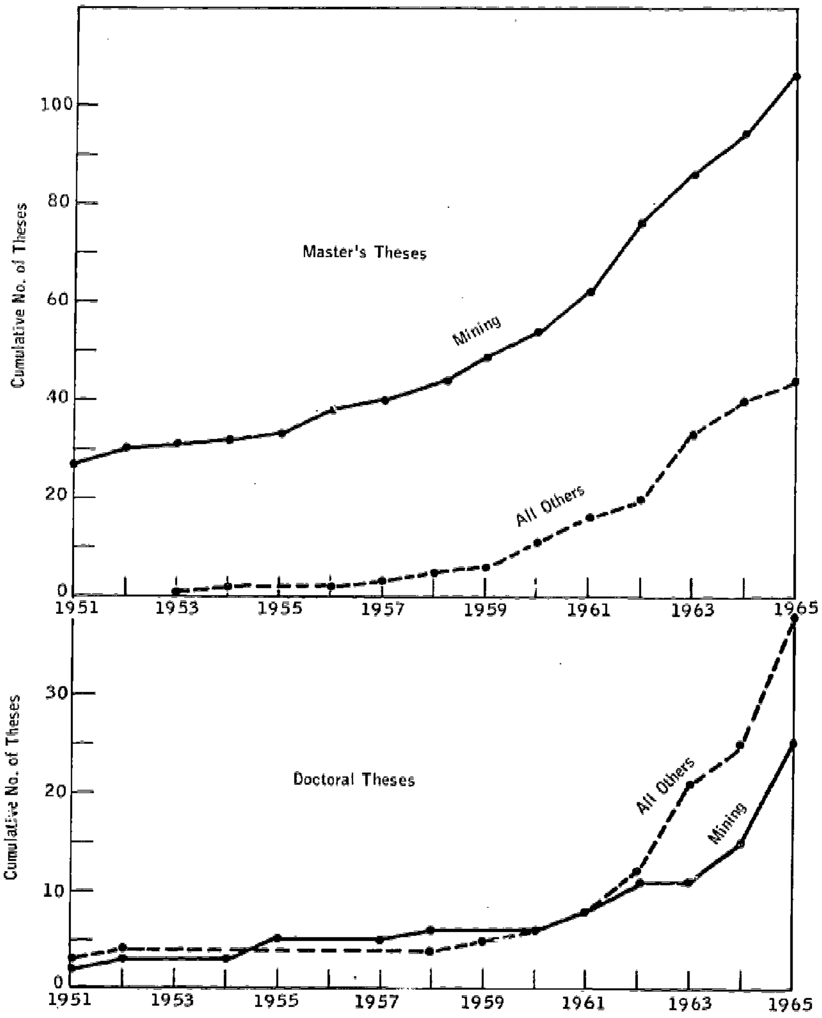

Figure 2
Cumulative number of theses by year. (Note change in ordinate scale between master's and doctoral theses.)

accounted for about as many doctoral theses as those of all other disciplines concerned with rock mechanics combined, but the combined output of the other disciplines has been increasing since 1962 and is now considerably greater than that of mining departments alone. The departments of civil engineering and mining engineering at the University of Illinois have each produced more doctoral dissertations on rock mechanics than any department at any other university. In the past five years, the University of California at Los Angeles and Stanford University have led in the production of rock mechanics doctoral theses by geology and geophysics departments, and the University of Texas has led in thesis production by a petroleum engineering department. It should be noted that research and education in rock mechanics by departments of civil engineering and petroleum engineering have been confined to relatively few institutions.

RESEARCH SCOPE

To determine where gaps exist in research, the Committee divided the theses into several categories according to subject area, type of measurement, etc. (Table 5 and Appendix F). The

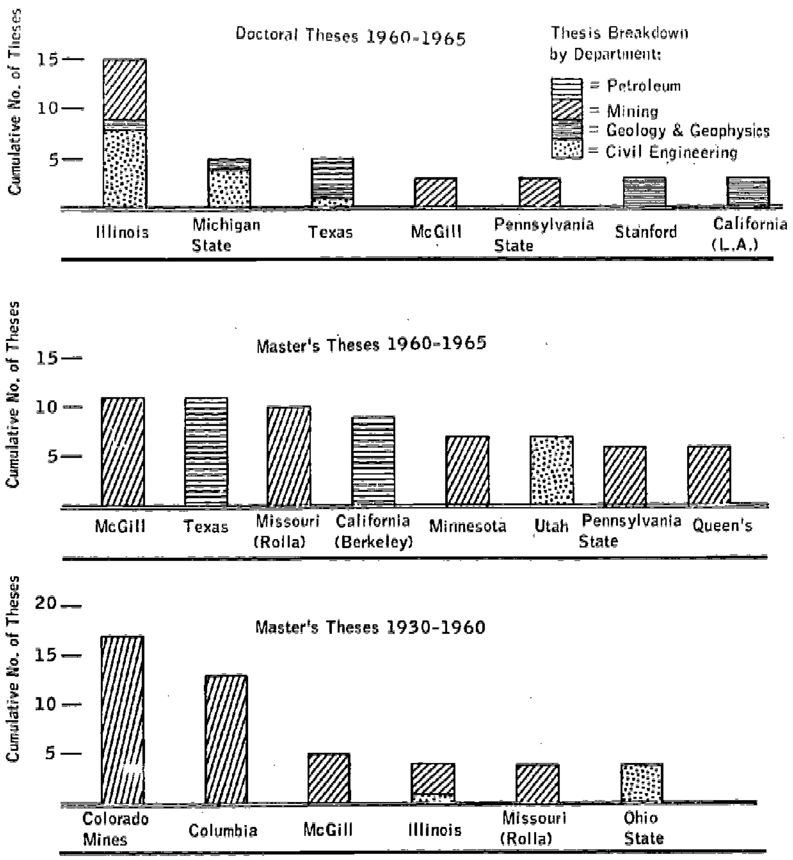

Figure 3
Number of theses in rock mechanics by leading institutions—before and after 1960.

Table 5

Scope of University Research in Rock Mechanics[a] (see Appendix B)

Categories	Number of Theses[b]			% of Total
	1961–65		1930–65	
	M.S.	Ph.D.	M.S. & Ph.D.	
1. Fundamentals (Theory and model studies)				
a. State of stress in the earth's crust	1	3	5	1.4
b. Stress-and-strain distribution	22	19	66	18.4
c. Failure theory	5	19	40	11.2
d. Stress-wave theory	2	4	7	2.0
				33.0
2. Measurements				
a. Laboratory				
(1) Static	44	19	98	27.7
(2) Dynamic	16	9	29	8.1
b. Field				
(1) Static	4	1	7	2.0
(2) Dynamic	4	1	7	2.0
				39.8
3. Applications				
a. Surface foundations, surface excavations, and natural slopes	5	2	8	2.2
b. Underground openings (including boreholes)	14	10	42	11.7
c. Rock as a construction material	1		1	0.3
d. Comminution				
(1) Drilling	18	2	28	7.8
(2) Blasting	2	2	8	2.2
(3) Crushing			2	0.5
e. Subsidence		1	4	1.1
f. Structural geology	1	4	5	1.4
				27.2
Total			357	100

[a] As indicated by thesis title.

[b] A thesis may be classified under more than one category.

theses were fairly evenly distributed among the three main categories: fundamentals, measurements, and applications.

However, it is the opinion of the Committee that within these categories the distribution of theses reflects certain imbalances. There has been heavy emphasis on laboratory measurement of rock properties and on applications related to underground openings. Emphasis on field measurements, structural geology, and investigation into the state of stress in the earth's crust has been light. Research effort directed toward applications to surface foundations, surface excavations, and rock as a construction material seems to be small in relation to the increasing activity in the United States on excavations for roads, buildings, dams, quarries, and so forth. Also, research on comminution and subsidence seems limited by comparison with the substantial research in other aspects of rock mechanics. The apparent lack of effort in stress-wave theory may simply reflect omission of these titles from the compilation rather than a real deficiency. Much of this type of research may be done in departments of physics and mechanics, which were inadvertently omitted from the survey.

RECOMMENDATIONS

The survey shows that teaching and research in rock mechanics are now being carried out at many universities in the United States and Canada and that this activity is well distributed geographically; to improve United States capabilities in rock mechanics still further and to continue to advance the science, the Committee recommends that:

1. Departments of geology, geophysics, petroleum engineering, and particularly civil engineering that do not now offer courses in rock mechanics consider establishing such courses.
2. Improvement in the educational and interdisciplinary aspects of rock mechanics be accomplished by periodic summer institutes, each limiting its attention to educators in either structural geology, mining engineering, civil engineering, petroleum engineering, or engineering geology.
3. Departments of civil engineering, geology, geophysics, mining engineering, and petroleum engineering increase their research in rock mechanics related to surface excavations, foundations, and rock as a construction material and that industry and federal agencies increase their financial support of university research in these areas.
4. Students seeking thesis topics in this field direct their attention to the following areas in which further work is needed:
    a. State of stress in the earth's crust
    b. Field measurements and analysis
    c. Applications to surface foundations and excavations
    d. Rock as a construction material
    e. Comminution
    f. Subsidence
    g. Structural geology

Industrial Research

The Committee conducted a survey of rock-mechanics research by United States industry during the period December 1964 to April 1965. Questionnaires (Appendix G) were sent to 235 companies representative of those segments of industry with an interest in rock mechanics. Responses were received from 139 companies (listed in Appendix H); they are subdivided into four groups: (1) consulting and contracting, (2) manufacturing, (3) mining, and (4) petroleum.

Of the responding companies, 49 percent are actively pursuing research in rock mechanics; 76 percent expressed interest in receiving more information from the Committee. Of the 68 companies doing research in rock mechanics, 28 percent fall into the consulting and contracting group, 25 percent are in manufacturing, 32 percent in mining, and 15 percent in the petroleum industry. The breakdown within each category is presented after Question I of Table 6.

Expenditures

How much money does industry spend on research in rock mechanics (Table 6, Question III)? Of the 68 companies doing research in rock mechanics, 44 provided information on expenditures. Enough figures were received to suggest the financial magnitude of such research. From 1963 to 1965, the total annual expenditure reported by these 44 companies for direct rock-mechanics research rose from approximately $800,000 to $1,200,000. The amount indicated as spent by mining companies in the period 1963 to 1965 was greatly exceeded by the amount spent by consulting and contracting companies; it should be noted, however, that much consulting and contracting work is done for mining companies.

Table 6

Industry Research in Rock Mechanics: Summary of Replies to Questionnaire[a]

Question	Consulting and Contracting			Manufacturing			Mining			Petroleum		
	Yes	No	% Yes	Yes	No	% Yes	Yes	No	% Yes	Yes	No	% Yes
I												
Research performed?	19	19	50	17	11	61	22	50	31	10	8	55
II												
Research planned?	1	18	5	1	10	9	10	40	20	0	8	0
IV[b]												
University research support?	4	29	12	6	13	31	6	53	10	8	5	62
Amount			$10,000						$5,000			$49,000
V												
Want further information?	33	4	89	15	1	94	48	12	80	10	2	83
III[b]												
Funding for research?												
	Direct		Related	Direct		Related	Direct		Related	Direct		Related
1963	$460,000		350,000	$35,000		189,000	$110,000		283,000	$170,000		94,000
1964	592,000		410,000	41,000		164,000	208,000		636,000	230,000		105,000
1965	681,000		445,000	49,000		281,000	247,000		477,000	265,000		105,000

[a] 136 replies were received to the 235 questionnaires sent.
[b] Only 39 companies responded to this question.

As shown in Figure 4, expenditures for research in rock mechanics during the interval 1963-1964 increased at the fastest rate in the mining industry; in the interval 1964-1965, however, all these industries were funding research in rock mechanics at approximately the same rate of increase.

The average unweighted expenditures for rock-mechanics research per company in each industry from 1963 to 1965 is as follows: 13 companies in the consulting and contracting group spent an average of $134,000 each; 6 petroleum companies averaged $110,000 each; 18 mining companies averaged $31,000 each; and 5 manufacturing companies averaged $25,000 each.

Although the annual expenditure by industry for research in rock mechanics has been relatively small, it has increased significantly since 1963; moreover, a number of companies indicate that they plan to initiate research programs in the near future. Many of these companies evidently have come to recognize the fact, long accepted by many other types of industry, that the long-range economic benefits from research generally exceed its cost. This attitude is clearly expressed in a number of the responses to the Committee's questionnaire.

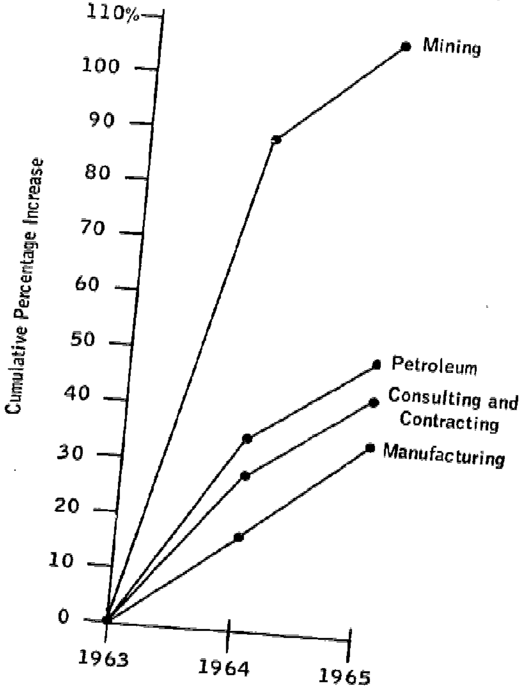

Figure 4
Industry—rate of annual expenditures for rock-mechanics research. 1963 has been used as the base year for computing cumulative percentage increase.

"Noncommercial" Research

While 49 percent of the responding companies conduct research in rock mechanics, as noted above, only 17 percent—fewer than eight companies in each group—support such research on a noncommercial basis, through grants and scholarships to universities (Table 6). Of the petroleum companies responding to the survey, 62 percent provide support for this type of research. These companies contribute funds to the American Petroleum Institute (API), an industrial association that provides and coordinates grants and fellowships to universities and other institutions for petroleum and related research.

Petroleum companies annually supply more than 75 percent of the total industrial funding of noncommercial research in rock mechanics. More than half of the $49,000 provided for this purpose by the petroleum industry in 1965, however, was channeled to mining schools. This relation gives emphasis to the Committee's recognition that an interdisciplinary approach is vital to the advancement of rock mechanics. The results of the API efforts indicate that mining, manufacturing, and consulting and contracting might receive more value for their research dollars if their funding also were channeled through or coordinated by a central association like API.

The Committee particularly supports the view shared by some participants in the survey, that industrial support for university research is good business.

Scope of Research

Although it is not possible from the data received to identify the entire scope of industrial research in rock mechanics, the responses clearly show that the scope is indeed very broad. The industrial research projects in rock mechanics (Table 7) indicate there is an emphasis on measurements (as there is in university projects). Moderate amounts of research are directed toward applications of rock mechanics to underground openings and to drilling, but research into other applications has received only slight attention. There appears to be little industrial research into the rock-mechanics problems related to surface excavations and foundations, to rock as a construction material, and to structural geology. These deficiencies are similar to those in university research, but are of greater concern to industry, which is so greatly involved in construction projects of all kinds in the United States. When applied to a large number of such projects, even small advances could result in significant savings in national resources.

Research into fundamentals has concentrated on the theory of stress-and-strain distribution and on the theory of failure;

Table 7

Industry Projects in Rock Mechanics
(Data following each topic refer to scope outlined on p. 4.)

CONSULTING AND CONTRACTING
- Drilling research—high-speed photography 2a(2), 3d(1)
- Drilling research—large-diameter boring machines 3b, 3d(1)
- Rock properties 2a(1), 2a(2), 2b(1), 2b(2)
- Rock properties—physical 2a(1), 2a(2), 2b(1), 2b(2)
- High-pressure studies 2a(2)
- High-pressure research—tectonophysics 1a, 3f
- Dynamic effects—<u>in situ</u> rock creep 2b(2)
- Dynamic effects—sonic velocity and attenuation 2a(2)
- Measurements—borehole extensometers 2b(1)
- Measurements—long-life load cells 2b(1)
- Geophysical logging studies 2b(2)
- Extraction of water—lunar geology 2a(1)
- Time deformation of pillars 2b(1)

MANUFACTURING
- Drilling research 3d(1)
- Drilling research—machine 3d(1)
- Drilling research—drillability 3d(1)
- Grinding and crushing 3d(3)
- Instrumentation 2a(1), 2a(2), 2b(1), 2b(2)

MINING
- Measurements—geophones used in microseismic detection 3b
- Measurements—photoelastic stress studies 1b, 2a(1)
- Measurements—photoelastic studies 1b, 2a(1)
- Measurements—microseismic studies 2b(2)
- Measurements—devices 2a(1), 2a(2), 2b(1), 2b(2)
- Measurements—extensometer and rock stress measurements 1b, 2b(1)
- Measurements—rock strains 2b(1)
- Crushing and grinding 3d(3)
- Rock stress 1b, 2b(1)
- Rock stress—magnitude and direction 1b, 3b
- Salt—flow characteristics 2a(1), 2b(1)
- Salt—mechanics of cutting with continuous miners 3b
- Solution—mining research 3b
- Response of rock to explosive shock 1d, 2a(2)
- Rock strain and stress around mine openings 1b, 2b(1), 3b
- Physical properties of rock for design 2a(1), 2a(2)
- Study and control of rock bursts 1b, 1c, 2b(2)
- Ground pressures 1b, 2b(1)
- Rock bolts including resin bonded types 3b

PETROLEUM
- Measurements—<u>in situ</u> 2b(1), 2b(2)
- Measurements—properties under triaxial compression 2a(1)
- Rock failure 1c
- Rock failure—brittle fracture 1c, 2a(1), 2a(2)
- Rock failure—development of a model 1c
- High-velocity impact 2a(2)
- Wave propagation 1d, 2b(2)
- Effect of stress and saturation on physical properties 2b(1)
- Rock fatigue 1c
- Petrofabrics 2a(1)

little has been done on the state of stress in the earth's crust. Actually there may be more work in progress on stress-wave theory than the survey indicates; some Committee members have knowledge of research on this subject that cannot be reported for reasons of national security.

RECOMMENDATIONS

In the light of the survey's findings on the status of industrial research in rock mechanics, the Committee recommends that:

1. Industry greatly increase its research toward development of fundamental concepts of rock mechanics.
2. Industry expand its research efforts on applications of rock mechanics to include:
    a. Surface excavations and foundations
    b. Rock as a construction material
    c. Field measurements
    d. Structural geology
3. Industry accomplish the preceding recommendations, in part, by:
    a. A several-fold increase of financial support to university research, and
    b. Employment of students majoring in rock mechanics or associated fields in part-time positions relating to the students' academic programs.
4. Mining companies and manufacturing companies coordinate basic research programs by forming associations similar to API; one such association might be organized and supported by the mining companies and another by equipment manufacturers, or one might be supported by all commercial interests but have subsidiary elements to deal with specific facets of rock mechanics.

Federal Research

During 1964 and 1965, the Committee surveyed research in rock mechanics conducted or supported by 10 agencies of the federal government. The survey identified 186 federal projects (Table 8 and Appendix I) directly related to rock mechanics. Certain other projects, such as areal seismological surveys and studies of the magnetic, electroconductivity, and thermal properties of rock, although they were in fields closely akin to rock mechanics, were not included because they do not appear to be strictly within the scope of the Committee's definition; it was also necessary to exclude projects related to national security.

Costs

Costs for both in-house and contract research were determined, and, where possible, official estimates of budgets for research in rock mechanics were obtained. The survey shows combined expenditures by government agencies for rock-mechanics research in 1965 of $6,800,000* ($4,800,000 in-house; $2,000,000 contract). Although the figure is approximate, it can be regarded as a lower limit of actual federal expenditures for this research.

As shown in Table 8, the Bureau of Mines, the National Science Foundation, the U.S. Air Force Office of Aerospace Research, the Corps of Engineers, support the greatest number of projects in rock mechanics. All projects were given equal weight in Tables 8 and 9. Because several agencies were reluctant to permit full disclosure of their funding, this analysis may not reflect accurately the magnitude of the effort or division of funds by agencies in the categories of research.

*The total of listed amounts in Appendix I is less than this figure because some information obtained by the Committee on certain in-house research could not be released for publication.

Table 8

Federal Projects in Rock Mechanics

Agency	Number of Projects
Atomic Energy Commission, U.S.	9
Commerce Department	
Bureau of Public Roads	6
Defense Department	
Air Force	
Office of Aerospace Research	25
Weapons Laboratory	16
Army	
Cold Regions Research and Engineering Laboratory	13
Corps of Engineers	24
Office of Civil Defense	1
Office of Research and Development	3
Navy	
Office of Naval Research	3
Weapons Laboratory	1
Interior Department	
Bureau of Mines	32
Bureau of Reclamation	9
Geological Survey	8
National Aeronautics and Space Administration	11
National Science Foundation	25
	186

Scope and Objectives

The scope of the federal research effort (Table 9 and Appendix F), is fairly evenly distributed among the three major categories of fundamentals, measurements, and applications. Moreover, within each category there appears to be an even distribution of effort. The apparent lack of research on rock as a construction material and on crushing may simply reflect the failure of the reporting agencies to identify correctly projects in these areas.

The similarity of several projects indicates some overlap of research by different agencies; in general, however, each agency has its own objective in conducting such research.

In addition to carrying out research similar to that being done by the universities and by industry, government agencies also conduct a moderate number of research projects involving field studies of various kinds.

Because certain military projects could not be included in the survey, the actual amount of government research on stress-wave theory and on dynamic field measurements could not be fully determined; it is probably greater than indicated.

Table 9

Scope of Federal Research in Rock Mechanics

Category	Number of Projects[a]	Percent of Total
1. Fundamentals (Theory and Model Studies)		
a. State of stress in the earth's crust	10	3
b. Stress-and-strain distribution	44	12
c. Failure theory	50	13
d. Stress-wave theory	31	8
		36
2. Measurements		
a. Laboratory		
(1) Static	54	15
(2) Dynamic	33	9
b. Field		
(1) Static	28	8
(2) Dynamic	31	8
		40
3. Applications		
a. Surface foundations, surface excavations, and natural slopes	24	6
b. Underground openings (including boreholes)	26	7
c. Rock as a construction material	1	0
d. Comminution		
(1) Drilling	8	2
(2) Blasting	11	3
(3) Crushing	0	0
e. Subsidence	2	1
f. Structural geology	18	5
	371	24

[a] A project may be listed in more than one category.

What are the reasons for government research in rock mechanics? Table 10 provides an approximate answer. Slightly over 40 percent of the number of federal research projects in rock mechanics is for military purposes (compared with 54 percent for all government research in fiscal year 1964*). Projects funded by military agencies investigating effects of nuclear explosions account for about 50 percent of the basic-research projects on rock properties. The number of research projects being sponsored for mining purposes is almost equal to the number for construction purposes. A rough idea of how much rock is moved in a year is indicated by the number of pounds of explosives used in the United States in 1963. About 50 percent, or 759,000,000 lb,

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*National Science Foundation, Federal Funds for Research, Development, and Other Scientific Activities, NSF 65-19, U.S. Government Printing Office, Washington, D.C. (1965), 177 pp.

Table 10

Primary Objectives of Federal Research in Rock Mechanics (by number of projects)

Objective	Number of Projects	Percent of Total
Effects of nuclear weapons	54	30
Civil engineering works	39	22
Basic research on rock properties	37	21
Mining operations	33	18
Earthquake seismology	7	4
Nuclear detection	4	2
Lunar studies	6	3
	180	100

was detonated in the mining of coal and metals. Of the remainder, construction accounted for 306,000,000 lb; quarrying and mining of nonmetals, 321,000,000 lb; other, 71,000,000 lb.*

Comment

In the light of the large amounts of funds that are spent and the larger amounts that will be spent on construction in the United States, research in rock mechanics related to civil engineering projects seems small. Fortunately, results of research in one problem often prove applicable to others; for example, improvements in methods of tunneling to obtain ore may apply directly to underground excavations for other purposes.

RECOMMENDATIONS

The survey indicates that government research in rock mechanics is small in amount, but diversified and relatively well balanced. The Committee recommends that:

1. Because research results often can be applied to many unrelated programs, the various government agencies

    a. Establish a coordinated system of information collection, retrieval, and dissemination of publications and progress reports on continuing research in this field, in cooperation with the Science Information Exchange (Smithsonian Institution), the Library of Congress, and the Defense Documentation Center;

    b. Provide for jointly sponsored projects, to reduce costs.

2. Federal research in rock mechanics be increased severalfold, in particular, research applicable to construction projects.

3. Federal agencies and universities undertake joint research projects in the general category of field measurements.

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*Bureau of the Census, 1965, Statistical Abstract of the United States, U.S. Government Printing Office, Washington, D.C. (1965), p. 807.

Conclusions

The general growth and interest in recent years in all aspects of education and research in rock mechanics is demonstrated by:

1. The proliferation since 1950 of symposia and conferences on rock mechanics
2. The large number of university departments (188) that offer courses, or parts of courses, on rock mechanics and the 30 universities that have graduate research assistants in rock mechanics
3. The increasing numbers of masters and doctoral theses on rock mechanics produced in all related disciplines—mining engineering, civil engineering, geology, geophysics, and petroleum engineering
4. The doubling of industry expenditures in the past three years, to a minimum of $1,700,000, and the substantial amount of funds, at least $6,800,000, spent by government in 1965 for research in rock mechanics
5. The increasing number of companies (66) and government agencies (10) that are doing research in this field

A qualitative evaluation of research programs verified the Committee's early conclusion that there is considerable variation of understanding about the meaning of the term rock mechanics. The Committee believes that there is a need for the various related disciplines to agree on a single definition of rock mechanics and hopes that the Committee's proposed definition (p. 3) will be accepted and used.

A study should be undertaken to determine the need for and consider the development of a curriculum for academic programs in rock mechanics. Clarification of curriculum needs might be achieved through summer institutes on rock mechanics organized for teachers of structural and engineering geology and of civil engineering, mining engineering, and petroleum engineering.

The research sponsored by universities, industry, and government stresses different aspects of rock mechanics and, on the whole, their work is complementary. This research has emphasized primarily measurements of rock properties, determination of fundamentals, and applications to mining. In view of the large expenditures for construction of highways, subways, dams, buildings, and so on, the research effort that is directed toward specific applications of rock mechanics to construction projects involving foundations, excavations, and rock as a construction material seems small; when applied to many projects, slight advances in technology could mean large savings in money and natural resources. In this regard, the Committee hopes that the specific research projects listed in Appendix J, which were recommended by the NAS-NRC Highway Research Board's Committee on Soil and Rock Properties (SGF-C2), will be undertaken in the near future.

Based on its experience and its national appraisal of present and potential use of rock mechanics, the Committee believes that the total effort in rock mechanics needs to be accelerated and that this can be done by increased contracts, grants, and fellowships to universities, increased cooperative projects among industry, universities, and government, and increased in-house research.

Because some research projects in rock mechanics, conducted by different groups, seem to be very similar, the Committee concluded that it would be desirable to coordinate rock-mechanics research. Such coordination would be particularly valuable to both the mining and manufacturing industries; considerable economic benefit might accrue to individual companies if some of their research funds were coordinated by a central organization similar to the American Petroleum Institute. In some phases of rock-mechanics research, such as rapid excavation, federal agencies could expedite the research effort and reduce costs by establishing a group to coordinate research, facilitate dissemination of information, decrease the possibility of duplication, and provide for jointly sponsored investigations.

Many of the preceding comments on problems of diverse educational curricula, duplication of research, and inefficiency indicate the need for better interdisciplinary communication in rock mechanics. This need might be satisfied by:

1. Establishment of a centralized computer, in which references to research on rock mechanics can be stored and from which lists of references can be retrieved
2. Publication of abstracts or a journal responsive to all disciplines
3. An annual interdisciplinary conference or symposium on rock mechanics

Appendixes

Appendix A

CONFERENCES ON ROCK MECHANICS*

1924	First Empire Mining and Metallurgical Congress, Great Britain
1927	Second Empire Mining and Metallurgical Congress, Canada
1930	Third Empire Mining and Metallurgical Congress, South Africa
1947	Symposium on Support of Rock Pressures in Coal Mining, Heerlen, Netherlands
1949	Fourth Commonwealth Mining and Metallurgical Congress, Great Britain
1950	International Conference on Rock Pressure Problems in Mining and Tunneling, Leoben, Austria
	International Congress on the Excavation of Galleries in Rock, Paris, France
1951	International Conference on Rock Pressure and Support in the Workings, Liège, Belgium
	First Annual Drilling Symposium, Minneapolis, Minn.
1952	Second Annual Drilling Symposium, Minneapolis, Minn.
1953	Fifth Commonwealth Mining and Metallurgical Congress, Australia
	Third Annual Drilling Symposium, Minneapolis, Minn.
1954	Fourth Annual Drilling Symposium, Minneapolis, Minn.
	Symposium on Pressure and Movement Related to Undermined Strata, Leeds, Great Britain
1955	Fifth Annual Drilling Symposium, Minneapolis, Minn.
	First Annual Symposium on Mining Research, Rolla, Mo.
1956	First Symposium on Rock Mechanics, Golden, Colo.
	International Strata Control Congress, Essen, Germany
	Sixth Annual Drilling Symposium, Minneapolis, Minn.
	Second Annual Symposium on Mining Research, Rolla, Mo.
1957	Second Symposium on Rock Mechanics: Behavior of Materials in the Earth's Crust, Golden, Colo.
	Sixth Commonwealth Mining and Metallurgical Congress, Canada
	Seventh Annual Drilling Symposium: Exploration Drilling, Minneapolis, Minn.
	Third Annual Symposium on Mining Research, Rolla, Mo.

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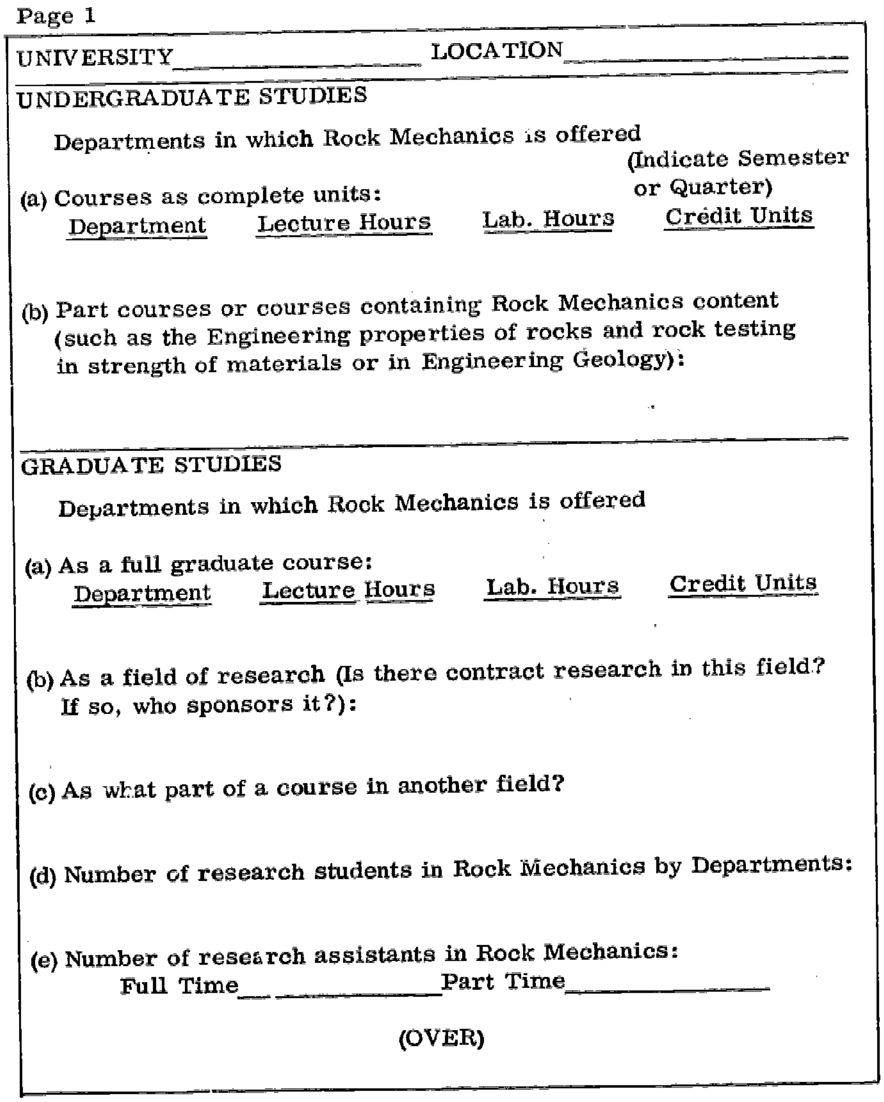
*The list is not intended to be exhaustive.

1958 International Strata Control Congress, Leipzig, East Germany
Symposium on Rock Mechanics, Division of Engineering Geology, Geological Society of America, St. Louis, Mo.
Eighth Annual Drilling Symposium: Drilling and Blasting, Minneapolis, Minn.
1959 Third Symposium on Rock Mechanics, Golden, Colo.
First Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
First International Mining Congress, Warsaw, Poland
Ninth Annual Drilling Symposium: Exploration Drilling, University Park, Pa.
Fifth Symposium on Mining Research, Rolla, Mo.
Symposium on Shaft Sinking and Tunneling, London, Great Britain
1960 Third International Conference on Strata Control, Paris, France
Rock Mechanics Session, American Institute of Mining, Metallurgical, and Petroleum Engineers, New York, N. Y.
Second Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
Tenth Annual Drilling Symposium: Drilling and Blasting, Golden, Colo.
1961 Second International Mining Congress, Prague, Czechoslovakia
Seventh Commonwealth Mining and Metallurgical Congress, South Africa and Rhodesia
Seventh International Congress on Large Dams, Rome, Italy
Third Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
Fourth Symposium on Rock Mechanics, University Park, Pa.
International Symposium on Mining Research, Rolla, Mo.
1962 Fourth Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
Fifth Symposium on Rock Mechanics, Minneapolis, Minn.
First Canadian Symposium on Rock Mechanics, Montreal, Canada
1963 Third International Mining Congress, Salzburg, Austria
Fifth Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
Rock Mechanics Session, American Institute of Mining, Metallurgical, and Petroleum Engineers, Dallas, Tex.
Eleventh Annual Drilling Symposium: Exploration Drilling, Golden, Colo.
Second Canadian Symposium on Rock Mechanics, Kingston, Canada
International Conference on State of Stress in the Earth's Crust, Santa Monica, Calif.
International Conference on Rapid Advance of Workings in Coal Mines, Liège, Belgium
First Conference on Drilling and Rock Mechanics, Austin, Tex.
1964 Fourth International Conference on Strata Control and Rock Mechanics, New York, N. Y.
Eighth Commonwealth Mining and Metallurgical Congress, Australia and New Zealand
Eighth International Congress on Large Dams, Edinburgh, Great Britain
Fifteenth Colloquium of the Austrian Regional Group of the International Society of Rock Mechanics, Salzburg, Austria (all previous ones were held in Salzburg)

1964 (cont'd)	Sixth Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
	Sixth Symposium on Rock Mechanics, Rolla, Mo.
1965	Fourth International Mining Congress, London, Great Britain
	Seventh Symposium on Rock Mechanics, University Park, Pa.
	Third Canadian Symposium on Rock Mechanics, Toronto, Canada
	Seventh Annual Conference, International Bureau of Rock Mechanics, Leipzig, East Germany
	Second Symposium on Salt, Cleveland, Ohio
	American Society for Testing and Materials Symposium on Rock Mechanics, Seattle, Wash.
	Second Conference on Drilling and Rock Mechanics, Austin, Tex.

Appendix B

SAMPLE QUESTIONNAIRE SENT TO UNIVERSITIES



Page 1

UNIVERSITY________________ LOCATION________________

UNDERGRADUATE STUDIES

Departments in which Rock Mechanics is offered

(a) Courses as complete units:

Department	Lecture Hours	Lab. Hours	(Indicate Semester or Quarter) Credit Units

(b) Part courses or courses containing Rock Mechanics content (such as the Engineering properties of rocks and rock testing in strength of materials or in Engineering Geology):

GRADUATE STUDIES

Departments in which Rock Mechanics is offered

(a) As a full graduate course:

Department	Lecture Hours	Lab. Hours	Credit Units

(b) As a field of research (Is there contract research in this field? If so, who sponsors it?):

(c) As what part of a course in another field?

(d) Number of research students in Rock Mechanics by Departments:

(e) Number of research assistants in Rock Mechanics:

Full Time________________ Part Time________________

(OVER)

Reverse side

Please list these topics (Indicate M.S. or Ph.D.):

Please list textbooks used (Indicate whether graduate or undergraduate):

Comments on course content:

Return to: Division of Earth Sciences
National Academy of Sciences–National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Appendix C

UNIVERSITY RESPONSES TO QUESTIONNAIRE

Key to symbols and abbreviations:

*	- undergraduate course
†	- graduate course
EG	- course on engineering geology or geotechnics
hv	- heavy: rock mechanics comprises more than 50 percent of course, although not designated "rock mechanics"
lt	- light: rock mechanics mentioned in several lectures
M	- course on mining
md	- medium: rock mechanics comprises 20-40 percent of course
P	- course on petroleum
PM	- course on properties of materials or soil mechanics
SG	- course on structural geology or tectonics
SM	- course on strength of materials and mechanics

Universities Offering Full or Partial Courses in Rock Mechanics (see Table 2, p.7)

<u>Full course or courses</u>:
Alabama, University of, Tuscaloosa, Ala.*†
Alaska, University of, College, Alaska*
Alberta, University of, Edmonton, Canada*
Arizona, University of, Tucson, Ariz.*†
Boston College, Weston, Mass.*†
California Institute of Technology, Pasadena, Calif.†
California, University of, Berkeley, Calif. *†
California, University of, Los Angeles, Calif.*†
Colorado School of Mines, Golden, Colo.*†
Columbia University, New York, N.Y.*†
Cornell University, Ithaca, N.Y.†
Florida State University, Tallahassee, Fla.†
Idaho, University of, Moscow, Idaho*†
Illinois, University of, Urbana, Ill.*†
Kentucky, University of, Lexington, Ky.*†
Laval, Université, Quebec, Canada†

Lawrence College, Appleton, Wis.*
Louisiana State University, Baton Rouge, La.†
Massachusetts Institute of Technology, Cambridge, Mass.†
Massachusetts, University of, Amherst, Mass.†
McGill University, Montreal, Canada*†
McMaster University, Hamilton, Canada†
Michigan State University, East Lansing, Mich.†
Michigan Technological University, Houghton, Mich.*†
Minnesota, University of, Minneapolis, Minn.*†
Missouri, University of, Rolla, Mo.*†
Montana School of Mines, Butte, Mont.*†
New Mexico Institute of Mining and Technology, Socorro, N.M.*
North Carolina, University of, Chapel Hill, N.C.†
Notre Dame, University of, Notre Dame, Ind.†
Nova Scotia Technological College, Halifax, Nova Scotia†
Ohio State University, Columbus, Ohio*
Pennsylvania State University, University Park, Pa.*†
Polytechnique, École, Montreal, Canada*
Queen's University, Kingston, Canada*†
Saskatchewan, University of, Saskatoon, Canada*
South Dakota School of Mines and Technology, Rapid City, S.D.*
Stanford University, Stanford, Calif.†
Texas Western College, El Paso, Tex.*
Texas, University of, Austin, Tex.†
Toronto, University of, Toronto, Canada*†
Utah, University of, Salt Lake City, Utah†
Virginia Polytechnic Institute, Blacksburg, Va.*†
Washington State University, Pullman, Wash.*†
Washington, University of, Seattle, Wash.*†
Wisconsin State College, Platteville, Wis.*
Wisconsin, University of, Madison, Wis.†

Partial course only:
Alfred University, Alfred, N.Y.* (EG-lt)
Amherst College, Amherst, Mass.* (SG-lt)
Antioch College, Yellow Springs, Ohio* (SG-lt)
Arizona State University, Tempe, Ariz.* (EG-md)
Arkansas, University of, Fayetteville, Ark.† (SG-md)
Augustana College, Rock Island, Ill.* (SG-lt)
Bates College, Lewiston, Me.* (SG-lt)
Beloit College, Beloit, Wis.* (SG-md)
Berea College, Berea, Ky.* (SG-lt)
Boston University, Boston, Mass.* (SG-md); † (EG-md)
Brigham Young University, Provo, Utah* (SG-lt; PM-lt)
British Columbia, University of, Vancouver, B.C., Canada* (SM-md)
Brooklyn Polytechnic Institute, Brooklyn, N.Y.* (PM-lt)
California State College, Los Angeles, Calif.* (SG-md)
California, University of, Davis, Calif.* (SG-lt)
Carnegie Institute of Technology, Pittsburgh, Pa.* (PM-lt)
Chattanooga, University of, Chattanooga, Tenn.* (SG-lt)
Cincinnati, University of, Cincinnati, Ohio* (EG-lt)
Clarkson College of Technology, Potsdam, N.Y.* (EG-md)
Clemson College, Clemson, S.C.* (PM-md)

Colorado State University, Fort Collins, Colo.* (EG-lt)
Colorado, University of, Boulder, Colo.* (SG-lt); † (SG-md)
Dartmouth College, Hanover, N.H.* (SG-lt)
DePauw University, Greencastle, Ind.* (SG-lt)
Dickinson College, Carlisle, Pa.* (EG-lt)
Emory University, Atlanta, Ga.* (SG-md; EG-md)
Fenn College, Cleveland, Ohio* (EG-md)
Florida, University of, Gainesville, Fla.* (EG-lt)
Georgia Institute of Technology, Atlanta, Ga.* (PM-lt); † (PM-lt)
Georgia, University of, Athens, Ga.* (SG-lt); † (SG-lt)
Gustavus Adolphus College, St. Peter, Minn.* (SG-lt)
Hamilton College, Clinton, N.Y.* (SG-lt)
Hanover College, Hanover, Ind.* (SG-lt)
Harvard University, Cambridge, Mass. † (SG-md; EG-md)
Hawaii, University of, Honolulu, Hawaii* (SG-lt); † (EG-lt)
Houston, University of, Houston, Tex.* (SM-lt)
Hunter College of the City University of New York, New York, N.Y.* (SG-lt)
Illinois Institute of Technology, Chicago, Ill.* (EG-md)
Indiana University, Bloomington, Ind.* (SG-lt)
Iowa State University, Ames, Iowa* (EG-lt)
Iowa, University of, Iowa City, Iowa* (SG-md); † (SG-md)
Kansas, University of, Lawrence, Kan.* (SG-lt)
Lamar State College of Technology, Beaumont, Tex.* (SG-md; EG-lt; PM-lt)
Long Beach State College, Long Beach, Calif.* (EG-lt)
Louisiana Polytechnic Institute, Ruston, La.* (SG-lt; SM-lt)
Maine, University of, Orono, Me.* (EG-lt)
Manitoba, University of, Winnipeg, Canada* (EG-hv)
Marshall University, Huntington, W. Va.* (PM-md)
Maryland, University of, College Park, Md.* (PM-lt); † (PM-lt)
Miami, University of, Coral Gables, Fla.* (EG-lt)
Mississippi State University, State College, Miss.* (SG-lt; EG-lt); † (SG-lt)
Monmouth College, Monmouth, Ill.* (SG-lt)
Montana State College, Bozeman, Mont.* (EG-lt)
Montana State University, Missoula, Mont.* (SG-lt); † (SG-lt)
Mount Allison University, Sackville, Canada* (SG-lt)
New Brunswick, University of, Fredericton, Canada* (SG-lt; EG-lt)
New Mexico State University, University Park, N.M.* (PM-lt)
New Mexico, University of, Albuquerque, N.M.* (SG-lt; EG-lt)
North Carolina State of the University of North Carolina at Raleigh, Raleigh, N.C.* (SG-lt; EG-lt)
North Dakota, University of, Grand Forks, N.D.* (M-hv)
Northwestern University, Evanston, Ill.* (SG-md; EG-md); † (SG-md)
Ohio Northern University, Ada, Ohio* (EG-lt)
Ohio University, Athens, Ohio* (EG-md)
Oklahoma State University, Stillwater, Okla. † (PM-lt)
Oklahoma, University of, Norman, Okla.* (SG-lt; SM-lt; PM-lt); † (SG-lt; SM-lt; PM-lt)
Old Dominion College, Norfolk, Va.* (SG-lt)
Oregon State University, Corvallis, Ore.* (SG-lt); † (SG-hv)
Oregon, University of, Eugene, Ore.* (SG-md); † (SG-md)
Pennsylvania, University of, Philadelphia, Pa.* (SG-md; PM-md)

Pittsburgh, University of, Pittsburgh, Pa.* (PM-lt; M-hv)
Pomona College, Claremont, Calif.* (SG-lt)
Princeton University, Princeton, N.J.* (EG-md)
Principia College, Elsah, Ill.* (SG-lt)
Purdue University, Lafayette, Ind.* (EG-lt); † (PM-md)
Rensselaer Polytechnic Institute, Troy, N.Y.* (SG-lt); † (SG-lt; EG-lt)
Rhode Island, University of, Kingston, R.I.* (SG-lt)l
Rice University, Houston, Tex.* (SM-lt)
Rutgers—The State University, New Brunswick, N.J.* (SG-lt; PM-md); † (PM-md)
St. Lawrence University, Canton, N.Y.† (SG-lt)
San Jose State College, San Jose, Calif.* (SG-md); † (SG-md)
Santa Clara, University of, Santa Clara, Calif.* (EG-lt)
South Carolina, University of, Columbia, S.C.* -(SG-md; EG-md); † (SG-hv)
Southern California, University of, Los Angeles, Calif.* (SG-lt; EG-lt); † (EG-lt)
Southern State College, Magnolia, Ark.* (SG-lt)
Southwestern Louisiana, University of, Lafayette, La.* (SG-lt); † (SG-lt)
Syracuse University, Syracuse, N.Y.* (SM-lt); † (SM-lt)
Texas A&M University, College Station, Tex.* (SG-lt; P-lt); † (SG-lt)
Texas Christian University, Fort Worth, Tex.* (SG-md); † (SG-md)
Texas Technological College, Lubbock, Tex.* (EG-lt)
Tufts University, Medford, Mass.* (SG-md)
Tulane University, New Orleans, La.* (EG-md; SM-lt)
Union College, Schenectady, N.Y.* (SG-md)
Utah State University, Logan, Utah* (PM-lt)
Vassar College, Poughkeepsie, N.Y.* (SG-lt)
Vermont, University of, Burlington, Vt.* (SG-lt; EG-lt)
Virginia Military Institute, Lexington, Va.* (EG-md; PM-lt)
Virginia, University of, Charlottesville, Va.* (EG-lt)
Washington University, St. Louis, Mo.* (EG-md); † (EG-md)
West Virginia University, Morgantown, W. Va.* (PM-lt)
Western Michigan University, Kalamazoo, Mich.* (SG-lt)
Western Reserve University, Cleveland, Ohio* (SG-lt); † (SG-lt)
Westminister College, Salt Lake City, Utah* (SG-lt)
Wheaton College, Wheaton, Ill.* (SG-lt)
Williams College, Williamstown, Mass.* (SG-md)
Windham College, Putney, Vt.* (SG-md)
Wisconsin State University, Superior, Wis.* (SG-lt)
Worcester Polytechnic Institute, Worcester, Mass.* (EG-md); † (EG-md)
Wyoming, University of, Laramie, Wyo.* (PM-lt)
Yale University, New Haven, Conn.† (SG-md)

Universities Not Offering Courses in Rock Mechanics

Arlington State College, Arlington, Tex.
Baylor University, Waco, Tex.
Bowling Green State University, Bowling Green, Ohio
Bradley University, Peoria, Ill.
Brooklyn College of the City University of New York, Brooklyn, N.Y.
Broome Technical Community College, Binghamton, N.Y.
Bucknell University, Lewisburg, Pa.

California, University of, Santa Barbara, Calif.
Carleton College, Northfield, Minn.
Carleton University, Ottawa, Canada
Case Institute of Technology, Cleveland, Ohio
Centenary College of Louisiana, Shreveport, La.
Chicago, University of, Chicago, Ill.
City College of the City University of New York, New York, N.Y.
City College of San Francisco, San Francisco, Calif.
Colby College, Waterville, Me.
Colorado College, Colorado Springs, Colo.
Connecticut, University of, Storrs, Conn.
Cooper Union, New York, N.Y.
Dalhousie University, Halifax, Nova Scotia
Dayton, University of, Dayton, Ohio
Delaware, University of, Newark, Del.
Denison University, Granville, Ohio
Detroit, University of, Detroit, Mich.
Drexel Institute of Technology, Philadelphia, Pa.
Drury College, Springfield, Mo.
Duke University, Durham, N.C.
Earlham College, Richmond, Ind.
Findlay College, Findlay, Ohio
Fort Hays Kansas State College, Hays, Kan.
Franklin Institute, Boston, Mass.
Fresno State College, Fresno, Calif.
Kansas State University, Manhattan, Kan.
Kent State University, Kent, Ohio
Lehigh University, Bethlehem, Pa.
Louisville, University of, Louisville, Ky.
Manhattan College, Bronx, N.Y.
Marquette University, Milwaukee, Wis.
Memorial University of Newfoundland, St. Johns, Newfoundland
Michigan, University of, Ann Arbor, Mich.
Middlebury College, Middlebury, Vt.
Midwestern University, Wichita Falls, Tex.
Minnesota, University of, Duluth, Minn.
Missouri, University of, Columbia, Mo.
Missouri, University of, Kansas City, Mo.
Montreal, University of, Montreal, Canada
Mount Holyoke College, South Hadley, Mass.
Muskingum College, New Concord, Ohio
Nebraska, University of, Lincoln, Neb.
Nevada, University of, Reno, Nev.
Newark College of Engineering, Newark, N.J.
New Hampshire, University of, Durham, N.H.
New York, State University of, Buffalo, N.Y.
New York, State University of, Cortland, N.Y.
New York, State University of (Harpur College), Binghamton, N.Y.
New York, State University of, New Paltz, N.Y.
New York University, New York, N.Y.
Northern Illinois University, Dekalb, Ill.
Norwich University, Northfield, Vt.
Oberlin College, Oberlin, Ohio

Ohio College of Applied Science, Cincinnati, Ohio
Oklahoma City University, Oklahoma City, Okla.
Portland State College, Portland, Ore.
Puget Sound, University of, Tacoma, Wash.
Queens College of the City University of New York, Flushing, N.Y.
Rochester, University of, Rochester, N.Y.
Rose Polytechnic Institute, Terre Haute, Ind.
St. Louis University, St. Louis, Mo.
San Diego State College, San Diego, Calif.
San Fernando Valley State College, Northridge, Calif.
Smith College, Northampton, Mass.
Southeast Missouri State College, Cape Girardeau, Mo.
Southern Mississippi, University of, Hattiesburg, Miss.
Sul Ross State College, Alpine, Tex.
Stephens Institute of Technology, Hoboken, N.J.
Swarthmore College, Swarthmore, Pa.
Tennessee, University of, Knoxville, Tenn.
Tulsa, University of, Tulsa, Okla.
Vanderbilt University, Nashville, Tenn.
Villanova University, Villanova, Pa.
Waterloo, University of, Waterloo, Canada
Wayne State University, Detroit, Mich.
Waynesbury College, Waynesbury, Pa.
West Texas State University, Canyon, Tex.
Western Ontario, University of, London, Canada
Western Washington State College, Bellingham, Wash.
Windsor, University of, Windsor, Canada
Wooster, College of, Wooster, Ohio

Appendix D

PUBLICATIONS USED FOR TEACHING ROCK MECHANICS

Number of departments using text is indicated in parentheses after reference.

Anderson, Paul, and G. M. Nordby, Introduction to Structural Mechanics, Ronald Press, New York (1960), 340 pp. (1)

Berry, G. L., and Brian Mason, Mineralogy– Concepts, Descriptions, Determinations, Freeman, San Francisco (1959), 612 pp. (1)

Billings, Marland P., Structural Geology, Prentice Hall, New York (1954), 2nd ed., 514 pp. (11)

Borg, Sidney F., Matrix-Tensor Methods in Continuum Mechanics, Van Nostrand, Princeton, N.J. (1963), 313 pp. (1)

Bridgman, Percy W., Studies in Large Plastic Flow and Fracture With Special Emphasis on the Effects of Hydrostatic Pressure, McGraw-Hill, New York (1952), 362 pp. (1)

Cleaves, A. B., and J. R. Schultz, Geology in Engineering, Wiley, New York (1955), 592 pp. (2)

Cook, M. A., The Science of High Explosives, Reinhold, New York (1958), 440 pp. (1)

Courant, Richard, and K. O. Friedrichs, Supersonic Flow and Shock Waves, Interscience, New York (1948), 464 pp. (1)

Crandall, Stephen H., and N. C. Dahl, eds., An Introduction to the Mechanics of Solids by Robert R. Archer and Others, McGraw-Hill, New York (1959), 444 pp. (1)

Dapples, E. C., Basic Geology for Science and Engineering, Wiley, New York (1959), 609 pp. (3)

deSitter, Lamoraal U., Structural Geology, McGraw-Hill, New York (1956), 552 pp. (13)

Dieter, George E., Mechanical Metallurgy, McGraw-Hill, New York (1961), 615 pp. (2)

Dobrin, M. B., Introduction to Geophysical Prospecting, McGraw-Hill, New York (1960), 2nd ed., 446 pp. (1)

Dove, R. C., and P. H. Adams, Experimental Stress Analysis and Motion Measurement—Theory, Instruments, Circuits, Techniques, C. E. Merrill Books, Columbus, Ohio (1964), 515 pp. (2)

Durelli, Augusto J., E. A. Phillips, and C. H. Tsao, Introduction to the Theoretical and Experimental Analysis of Stress and Strain, McGraw-Hill, New York (1958), 498 pp. (1)

Ewing, William M., W. S. Jardetzky, and F. Press, Elastic Waves in Layered Media, McGraw-Hill, New York (1957), 380 pp. (1)

Freudenthal, Alfred M., The Inelastic Behavior of Engineering Material and Structures, Wiley, New York (1950), 587 pp. (1)

Frocht, Max M., Photoelasticity, Wiley, New York (1941, 1948), 2 vols. (7)

Goldstein, Herbert, Classical Mechanics, Addison-Wesley, Reading, Mass. (1950), 399 pp. (1)

Green, Albert E., and W. Zerna, Theoretical Elasticity, Clarendon Press, Oxford (1954), 442 pp. (1)

Handin, J., and D. Griggs, eds., Rock Deformation, A Symposium:, Geological Society of America, New York (1960), 382 pp. (6)

Henshaw, J. T., ed., Symposium on Supersonic Engineering, Heinemann, London (1961), 264 pp. (1)

Hetényi, M., ed., Handbook of Experimental Stress Analysis, Wiley, New York (1950), 1,077 pp. (2)

Hill, R., Mathematical Theory of Plasticity, Clarendon Press, Oxford (1950), 356 pp. (1)

Hills, E. S., Elements of Structural Geology, Wiley, New York (1963), 483 pp. (8)

Houwink, Roelof, Elasticity, Plasticity, and Structure of Matter, 2nd ed., Harren Press, Washington, D.C. (1953), 368 pp. (1)

Isaacson, E. de St.Q., Rock Pressure in Mines, 2nd ed., Mining Publications, London (1962), 212 pp. (18)

Jaeger, J. C., Elasticity, Fracture, and Flow with Engineering and Geologic Applications, 2nd ed., Wiley, New York (1962), 208 pp. (21)

Jumikis, A. R., Soil Mechanics, Van Nostrand, Princeton, N.J. (1962), 791 pp. (1)

Karol, R. H., Soils and Soils Engineering, Prentice Hall, Englewood Cliffs, N.J. (1960), 194 pp. (1)

Kinney, J. S., Indeterminant Structural Analysis, Addison-Wesley, Reading, Mass. (1957), 655 pp. (1)

Kittel, C., Introduction to Solid State Physics, Wiley, New York (1953), 396 pp. (1)

Kolsky, H., Stress Waves in Solids, Dover, New York (1963), 213 pp. (1)

Krynine, D. P., and W. R. Judd, Principles of Engineering Geology and Geotechnics, McGraw-Hill, New York (1957), 730 pp. (15)

Lee, G. H., An Introduction to Experimental Stress Analysis, Wiley, New York (1950), 319 pp. (7)

Legget, R. F., Geology and Engineering, McGraw-Hill, New York (1962), 884 pp. (9)

Lekhnitskii, S., Theory of Elasticity of an Anisotropic Elastic Body, Holden-Day, San Francisco (1963), 404 pp. (1)

Lubahn, J. D., and R. P. Felgar, Plasticity and Creep of Metals, Wiley, New York (1961), 608 pp. (1)

Mueller, L., Der Felsbau, Vol. 1, F. Enke, Stuttgart, Germany (1963) (1)

Nádai, Arpad, Theory of Flow and Fracture of Solids, 2nd ed., McGraw-Hill, New York (1963), Vol. 1 (9)

Nara, Harry R., ed., Vector Mechanics for Engineers, Vol. 1, Statistics, Vol. 2, Dynamics, Wiley, New York (1962) (2)

Nevin, Charles M., Principles of Structural Geology, 4th ed., Wiley, New York (1949), 410 pp. (1)

Nye, J. F., Physical Properties of Crystals, Their Representation by Tensors and Matrices, Clarendon Press, Oxford (1957), 322 pp. (2)

Poldervaart, Arie, ed., Crust of the Earth (A Symposium), Waverly Press, Baltimore (1955), 762 pp. (1)

Popov, E. P., Mechanics of Materials, Prentice-Hall, New York (1952), 441 pp. (2)

Prager, William, Introduction to the Mechanics of Continua, Ginn, Boston (1961), 230 pp. (1)

Proctor, R. V., and T. L. White, Rock Tunneling With Steel Supports, Commercial Shearing and Stamping Co., Youngstown, Ohio (1946), 271 pp. (1)

Scheideger, A. E., Principles of Geodynamics, 2nd ed., Springer, Berlin (1963), 362 pp. (1)

Sechler, E. E., Elasticity in Engineering, Wiley, New York (1952), 419 pp. (1)

Seely, Fred B., and J. O. Smith, Advanced Mechanics of Materials, 2nd ed., Wiley, New York (1942), 680 pp. (2)

Sokolnikoff, I. S., Mathematical Theory of Elasticity, 2nd ed., McGraw-Hill, New York (1956), 476 pp. (4)

Spangenberg, Karl R., Fundamentals of Electron Devices, McGraw-Hill, New York (1957), 505 pp. (1)

Spangler, Merlin G., Soil Engineering, 2nd ed., International Textbook, Scranton, Pa. (1951), 483 pp. (1)

Spaulding, J., Deep Mining, Mining Publications, London (1949), 405 pp. (3)

Talobre, Joseph, La Mécanique des Roches, Dunod, Paris (1957) (1)

Teng, Wayne C., Foundation Design, Prentice-Hall, Englewood Cliffs, N.J. (1962), 466 pp. (1)

Timoshenko, Stephen, and J. N. Goddier, Theory of Elasticity, 2nd ed., McGraw-Hill, New York (1951), 506 pp. (5)

Timoshenko, Stephen, and D. H. Young, Elements of Strength of Materials, 4th ed., Van Nostrand, Princeton, N.J. (1962), 377 pp. (1)

Trefethen, Joseph M., Geology for Engineers, Van Nostrand, New York (1959), 632 pp. (8)

Turner, Francis J., and L. E. Weiss, Structural Analysis of Metamorphic Tectonites, McGraw-Hill, New York (1963), 545 pp. (3)

Vlack, Lawrence, H., van, Elements of Materials Science—An Introductory Text for Engineering Students, 2nd ed., Addison-Wesley, Reading, Mass. (1964), 445 pp. (1)

Walton, William H., ed., Conference on Non-Metallic Brittle Materials, London, Interscience, New York (1958), 492 pp. (2)

Wang, Chi-teh, Applied Elasticity, McGraw-Hill, New York (1953), 357 pp. (1)

Zeldovich, I͡Akov B., and A. S. Kompancets, Theory of Detonation, Academic Press, New York (1960), 284 pp. (1)

Appendix E

THESES IN ROCK MECHANICS BY SCHOOL, THROUGH 1965

Numbers at left have been arbitrarily assigned for this report only.

*Following institution name indicates that copies of doctoral dissertations are available from University Microfilms, Inc., 300 N. Zeeb Road, Ann Arbor, Mich.

Code following thesis data corresponds to paragraphing in tabular material on p. 4.

ALBERTA, UNIVERSITY OF

Master's Thesis

Department of Geology

1.	1965	G. Muecke	Fracture analysis in the Canadian Rocky Mountains (M.S. in progress). 3f

CALIFORNIA, UNIVERSITY OF (BERKELEY)*

Master's Theses

Department of Mineral Technology

2.	1962	J. J. Reed	An analysis of mine opening failures by means of models (M.S.). 1c
3.	1961	M. S. King	Shear wave velocity in rocks at simulated overburden pressures (M.S.). 2a(2)
4.	1963	B. Banthia	Ultrasonic shear-wave velocities in rocks subjected to simulated overburden pressure and internal pore pressure (M.S.). 2a(2)
5.	1963	G. W. Dean	Changes in the specific properties of porous rocks subjected to simulated reservoir pressures and high temperatures (M.S.). 2a(1)
6.	1963	H. M. Ewoldsen	A study of the relations between laboratory and field tests on the Domengine sandstone (M.S.). 2a(1), 2a(2), 2b(1), 2b(2)

7. 1963 R. C. Hartmann — Fracture characteristics of sandstones heated to high temperatures (M.S.). 2a(1)

8. 1963 W. E. Switzer — Model study of a shear-wave logging tool (M.S.). 2a(2), 2b(2)

9. 1964 D. S. Cahn — Breaking of solids by laser irradiation (M.S.). 2a(2)

10. 1964 M. Maleki — Demonstrations of presence of dead-end pores in carbonate reservoir rocks (M.S.). 2a(1)

11. 1964 M. M. Mehta — Thermal alterations of sandstone (M.S.). 2a(1), 2a(2)

Doctoral Theses

Department of Mineral Technology

12. 1955 J. J. Reed — Mine opening stabilization by stress redistribution (Ph.D.). 1b, 3b

13. 1964 M. S. King — Wave velocities and dynamic moduli of sedimentary rocks (Ph.D.). 2a(2)

CALIFORNIA, UNIVERSITY OF (LOS ANGELES)*

Master's Theses

Department of Geology

14. 1958 H. C. Heard — The brittle to ductile transition in Solenhofen limestone as a function of temperature, confining pressure, and interstitial pressure (M.A.). 1c, 2a(1)

15. 1960 R. E. MacDougall — A model study of an applied potential survey concerning the deep crust in Massachusetts (M.A.). 1a

Doctoral Theses

Department of Geology

16. 1962 H. C. Heard — The effect of large changes in strain rate in experimental deformation of rocks (Ph.D.). 1b, 1c, 2a(1)

17. 1963 N. L. Carter — Experimental deformation and recrystallization of quartz (Ph.D.). 1b, 2a(1)

18. 1963 C. B. Raleigh — Fabrics of naturally and experimentally deformed olivine (Ph.D.). 1b, 2a(1)

COLORADO SCHOOL OF MINES

Master's Theses

Department of Mining Engineering

19. 1933 F. C. Carstarphen — A mathematical theory of the stresses and strains in the wall of tunnels, and related problems (M.S. 539). 1b

20.	1941	R. T. Gallagher	A method of determining subsidence in mining with particular reference to block caving (M.S. 599). 3e
21.	1943	A. D. Kafadar	An investigation of the stress distribution around underground openings by photoelastic methods (M.S. 601). 1b
22.	1943	S. M. Seyhun	Stresses caused by the broken rock of an underground opening (M.S. 603). 1b
23.	1947	A. Choh-Yi	A study of subsidence caused by underground mining with special emphasis on angle of break (M.S. 614). 3e
24.	1948	W.R. McCutchen	The behavior of rocks and rock masses in relation to military geology (M.S. 642). 3a, 3b
25.	1949	G.E. Hesselbacher	A method for the determination of stresses around an opening under impact loads (M.S. 656). 1b
26.	1950	J. P. Cogan	The mechanics of rock failure (M.S. 669). 1c
27.	1951	G. S. Landrith	A method and study of the stresses around an opening under concentrated static loads using stresscoat (M.S. 716). 1b
28.	1951	A. H. Kapadia	Correlation of scleroscope hardness with physical and elastic properties of rock (M.S. 728). 2a(1)
29.	1951	J. E. Veatch	Photoelastic and stresscoat studies of the stresses around underground arch-type openings (M.S. 717). 1b
30.	1952	R. Segal	An investigation of elastic properties of rock under uniaxial and triaxial compression tests (M.S. 756). 2a(1)
31.	1953	P. Böck	An investigation of relations among bulk modulus of rocks, energy stored, and stresses applied (M.S. 774). 2a(1)
32.	1955	J.S. Fairbairn	Photoelastic investigation of pillar stresses (M.S. 829). 1b
33.	1956	S. Tandanand	Effect of bit shape on the cutting action of percussion-type bits (M.S. 837). 3d(1)
34.	1958	V. M. Garcia	Physical properties of mine rocks and their effect on percussive drillability (M.S. 882). 2a(1), 3d(1)
35.	1959	J. F. Abel, Jr.	Ice tunnel closure phenomena (M.S. 893). 1b, 1c

36.	1961	N. M. Raju	Elastic, static, and dynamic behavior of layered Rifle shale and coal (M.S. 9[illegible]1). 2a(1), 2a(2)
37.	1961	B. Rufus	Investigation of the influence of the dimensions and layering of rock specimens, on the compressive strength (M.S. 916). 2a(1)
38.	1962	M. A. Razvi	The effect of moisture on the compressive strength and modulus of elasticity of limestone (M.S. 953). 2a(1)

Doctoral Theses

Department of Mining Engineering

39.	1950	M. J. Pandya	Stress analysis applied to rock failure around underground openings (D.Sc. 682). 1b, 1c
40.	1955	H. K. VanPoollen	A photoelastic investigation of the relationship between stresses around mine openings and resulting failure (D.Sc. 811). 1b, 1c
41.	1958	D. O. Rausch	Studies of ice excavation (D.Sc. 865). 3b

COLUMBIA UNIVERSITY*

Master's Theses

Department of Geology

42.	1963	V. P. Amy	Effect of strain rate on the strength of brittle rocks (M.A.). 1b, 1c, 2a(1)
43.	1963	E. Karp	Experimental deformation of Crown Point limestone; a study of prestraining and strain rate effects and the nature of recoverable deformation (M.A.). 1b, 1c, 2a(1)
44.	1964	R. T. Faill	Deformational modes of behavior of Crown Point limestone as a function of confining pressure and total strain (M.A.). 1b, 1c, 2a(1)

School of Mines

45.	1931	A. W. Ducsay	Relation of type of break to depth of overburden in mine subsidence (E.M.). 2b(1), 2b(2), 3e
46.	1931	R. H. Knapp	The application of a stroboscope to a laboratory testing machine (E.M.). 2a(1)
47.	1940	H. J. Victory	Time effect on mine roof behavior (M.S.). 3b

48.	1941	T. Ertl	Report on investigations into the mechanics of coring and the mechanical properties of weak rocks (M.S.). 2a(1)
49.	1941	R. V. Taborelli	An investigation into the effect of time on rock failure (M.S.). 1c, 2a(1)
50.	1942	A. A. Yenisey	"Rock burst" causes and prevention (E.M.). 1c, 3b
51.	1947	J. M. C. Gaffron	A project on the shaped charges (E.M.). 3d(1), 3d(2)
52.	1948	P. B. Nalle	An investigation of dynamic methods for determining Young's modulus and the feasibility of determining the stress in rock structures by such methods (M.S.). 1b, 2a(2)
53.	1949	H. R. Cohen	Vibration as a means of breaking rock (E.M.). 1c, 2a(2)
54.	1949	M. Mohtashami	Summary of long blast-hole diamond drilling (M.S.). 3d(1), 3d(2)
55.	1951	D. L. Rainey	The physical properties of geologic materials and their relations to rock bursts (M.S.). 1c, 2a(1), 3b
56.	1956	P. G. Zambas	An investigation of the relations between the drillability of various rocks and their respective physical properties (M.S.). 2a(1), 3d(1)
57.	1959	E. J. Brebner	Investigations into the use of ultrasonic testing equipment in the detection of rock failure (M.S.). 2a(1), 2b(1)

Doctoral Theses

Department of Geology

58.	1965	B. Voight	Structural studies in west-central Vermont (Ph.D.). 1b, 1c, 3f

School of Mines

59.	1948	L. A. Panek	Stresses about mine openings (Ph.D.). 1b, 3b

GEORGIA INSTITUTE OF TECHNOLOGY

Doctoral Theses

School of Civil Engineering

60.	1963	A. E. Schwartz	An investigation of the strength of rock (Ph.D.). 2a(1)
61.	1965	B. B. Mazanti	Effect of the intermediate principal stress on strength of rock (Ph.D. in progress). 2a(1)

HARVARD UNIVERSITY

Doctoral Theses

Department of Geological Sciences

62.	1935	K. K. Welker	Rock failure in deep mines; field and experimental studies (Ph.D.). 1c, 2a(1), 2b(1), 3b
63.	1936	N. A. Haskell	A study of the mechanics of deformation of granitic rocks (Ph.D.). 1b, 1c, 2a(1)
64.	1952	E. C. Robertson	An experimental study of flow and fracture in rocks (Ph.D.). 1b, 1c, 2a(1)
65.	1960	P. LeComte	Creep and internal friction of rock salt (Ph.D.). 1b, 1c, 2a(1)

ILLINOIS, UNIVERSITY OF*

Master's Theses

Department of Civil Engineering

66.	1953	T. S. Fry	Preliminary study of the effect of moisture on the frictional resistance of minerals (M.S.). 2a(1)

Department of Geology

67.	1964	P. Kraatz	Rockwell hardness as an index property of rocks (M.S.). 2a(1)

Department of Mining, Metallurgy, and Petroleum Engineering

68.	1952	R. D. Caudle	A correlation of stress concentrations around certain mine openings for simple geological conditions from mine models (M.S.). 1b
69.	1956	H. C. Rolseth	Study of the strength properties of rock salt (M.S.). 2a(1)
70.	1957	J. M. Cleary, Jr.	A laboratory study of the elastic properties of sandstone (M.S.). 2a(1)
71.	1962	M. B. Mirza	Photoelastic study of a stress distribution around a vertical crack in a mine roof beam (M.S.). 1b, 3b
72.	1964	H. Pulpan	Calculation of tectonic stresses from hydraulic well fracturing data (M.S.). 1a

Doctoral Theses

Department of Civil Engineering

73.	1961	H. M. Horn	An investigation of the frictional characteristics of minerals (Ph.D.). 2a(1)
74.	1961	J. P. Murtha	Discrete mass mathematical models for one-dimensional stress waves (Ph.D.). 1d

75.	1963	S. L. Paul	Interaction of plane elastic waves with a cylindrical cavity (Ph.D.). 1b
76.	1963	T. Yoshihara	Interaction of plane elastic waves with an elastic cylindrical shell (Ph.D.). 1b
77.	1964	J. H. Withers	Sliding resistance along discontinuities in rock masses (Ph.D.). 1c
78.	1965	E. J. Cording	Predicted and observed behavior during construction of three large underground openings (Ph.D. in progress). 1b, 1c, 2a(1), 2a(2), 2b(1), 2b(2), 3b
79.	1965	R. P. Miller	Engineering classification and index properties for intact rock (Ph.D.). 2a(1), 2a(2), 3a, 3b
80.	1965	S. F. Reyes	Elastic-plastic analysis of underground openings by the finite element method (Ph.D.). 1b, 1c

Department of Geology

81.	1965	F. D. Patton	Multiple modes of shear failure in rock and related materials (Ph.D.). 1c, 2a(1), 3a

Department of Mining, Metallurgy, and Petroleum Engineering

82.	1952	G. B. Clark	Propagation of small shock waves from a spherical cavity in an infinite isotropic elastic medium (Ph.D.). 1b, 1d
83.	1964	L. Adler	Curved beam theory applied to opening design (Ph.D.). 1b, 1c, 3b
84.	1964	R. W. Heins	Studies of the Rehbinder effect by the Rehbinder-Kuznetsov pendulum (Ph.D.). 2a(1)
85.	1964	G. E. Ratti	Analysis of a continuous plate (Ph.D.). 1b, 1c, 3b
86.	1965	M. B. Mirza	Stress distribution in cracked mine roofs (Ph.D. in progress). 1b, 3b
87.	1965	J. Sturgal	Aspects of underground pressures on surface features of the earth (Ph.D. in progress). 1a, 3f
88.	1965	F. D. Wang	Effects of fluid environment on the strength of geological materials (Ph.D. in progress). 1a

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

<u>Doctoral Thesis</u>

Department of Geology and Geophysics

89.	1965	B. W. Paulding	Crack growth during brittle fracture in compression (Ph.D.). 1c

McGILL UNIVERSITY

Master's Theses

Department of Mining Engineering and Applied Geophysics

90.	1954	E. L. Cameron	An investigation into some physical properties of rocks and their relationship to pressure problems in mines (M.S.). 2a(1), 2a(2), 3b
91.	1955	C. A. Macaulay	The relationship between the physical properties of rocks and underground mining conditions (M.S.). 2a(1), 2a(2), 3b
92.	1956	W. P. H. Cairnes	A study of the rupture of rocks under stress with special reference to mine excavations (M.S.). 2a(1), 3b
93.	1957	W. D. Ortlepp	An experimental investigation into certain aspects of rock failure (M.S.). 1c, 2a(1)
94.	1959	J. J. L. Davies	Pillars—applications and limitations in underground mining (M.S.). 3b
95.	1960	J. E. Udd	The physical properties of the Elliot Lake ore-bearing conglomerate (M.S.). 2a(1)
96.	1961	H. Tun	Elastic and strength properties of Elliot Lake quartzites (M.S.). 2a(1)
97.	1961	R. B. Sutherland	A comparison between the sonic and static elastic moduli of rocks (M.S.). 2a(1), 2a(2)
98.	1963	D. E. Gill	Uniaxial compression as an element in a classification of rocks (M.S.). 2a(1)
99.	1964	O. B. Nair	Photoelastic analysis of stress in and around mine pillars (M.S.). 1b, 3b
100.	1965	M. Aslam	Coupling relations in blasting-dynamic testing (M.S. in progress). 3d(2)
101.	1965	M. A. Mahtab	Determination of field stresses around elliptical openings (M.S. in progress). 1b
102.	1965	M. J. Royea	A study of energy dissipation in Sullivan Mine (COMINCO) and other rocks (M.S. in progress). 2b(2)
103.	1965	T.-M. Shih	The physical properties of a Gaspe skarn (M.S.). 2a(1)
104.	1965	K. Wilson	A review of compression testing procedure with reference to a Trenton limestone (M.S. in progress). 2a(1)
105.	1965	Y.-S. Yu	The physical properties of "Sigma" porphyry (M.S.) 2a(1)

Doctoral Theses

Department of Mining Engineering and Applied Geophysics

106.	1965	D. F. Coates	Pillar loading (tentative title–Ph.D. in progress). 3b
107.	1965	D. E. Gill	Dynamic properties of rock (tentative title—Ph.D. in progress). 2a(2)
108.	1965	J. E. Udd	Stresses in a crown pillar with particular reference to fracture (tentative title–Ph.D. in progress). 1b, 1c, 3b

MICHIGAN STATE UNIVERSITY*

Master's Thesis

Department of Civil Engineering

109.	1962	A. B. Raman	Elastic-plastic transition tests on various rock types (M.S.). 2a(1)

Doctoral Theses

Department of Civil Engineering

110.	1963	A. M. Chowdiah	Stress and strain distribution around openings in underground salt formations (Ph.D.). 1b, 3b
111.	1963	A. Dahir	Analysis of elastic, plastic and visco-elastic behavior of a model salt cavity in a continuous media (Ph.D.). 1b, 1c
112.	1963	O. A. Gheida	Effects of stress on ultrasonic wave velocities in rock salt (Ph.D.). 2a(2)
113.	1965	S. Sakurai	Time and stress-strain relationship in a continuous media (Ph.D. in progress). 1b, 1c

Department of Geology

114.	1965	V. S. Griffin	Mesoscopic and microscopic fabric relationships across the Catoctin Mountain—Blue Ridge anticlinorium of central Virginia (Ph.D.). 3f

MICHIGAN TECHNOLOGICAL UNIVERSITY

Master's Theses

Department of Mining Engineering

115.	1950	R. R. Smith	The effects of compression and impact on the rocks of the Marquette, Gogebic, and Menominee Ranges (M.S.). 2a(1)
116.	1962	C. C. Hanninen	A study of deformation at the periphery of a mine opening related to stoping activity (M.S.). 3b

MINNESOTA, UNIVERSITY OF*

Master's Theses

Department of Mineral Engineering

117.	1958	T. B. Johnson	Analysis of the effect of variation in diameter and cutting speed on instantaneous stress fluctuations in a rotary rock cutting tool (M.S.). 3d(1)
118.	1959	C. W. Berry	Determination of the force-displacement characteristic of rocks (M.S.). 2a(1), 3d(1)
119.	1962	D. R. Reichmuth	Correlation of force-displacement data with physical properties of rock for percussive drilling systems (M.S.). 2a(1), 3d(1)
120.	1963	B. R. Stephenson	Measurement of dynamic force-penetration characteristics in Indiana limestone (M.S.). 2a(2), 3d(1)
121.	1965	J. J. Chen	The effect of confining pressure on the force-displacement characteristic of some saturated rocks (M.S.). 2a(1), 3d(1)
122.	1965	B. Haimson	The influence of bit impact velocity on the force-displacement characteristic of rocks (M.S.). 2a(1), 3d(1)
123.	1965	W. A. Hustrulid	A study of energy transfer to rock and prediction of drilling rates in percussive drilling (M.S.). 3d(1)

Doctoral Theses

Department of Mineral Engineering

124.	1965	P. F. Gnirk	An analysis of explosive crater formation in blasting (Ph.D.). 3d(2)
125.	1965	H. F. Iman	A visco-elastic analysis of mine subsidence in horizontally laminated strata (Ph.D.). 3e

MISSOURI, UNIVERSITY OF (ROLLA)

Master's Theses

Department of Mining Engineering

126.	1946	W. E. Lewis	The mechanical properties of mine rocks and a standardized test procedure for their determination (M.S.). 2a(1)
127.	1947	J. W. Snider	The effects of temperature on mine rocks (M.S.). 2a(1)
128.	1951	S. S. Aybat	Stress analysis of thin-bedded mine roofs subjected to evenly distributed lateral load and supported by bearing pillars (M.S.). 1b, 3b

129.	1958	N. B. Haubold	A preliminary investigation of strains and fracturing in small hydro-stone beams due to impact loading (M.S.). 1b, 1c
130.	1960	S. S. M. Chan	Physical property tests of rock, centrifugal tests and the design of underground mine openings (M.S.). 2a(1), 3b
131.	1960	I. Dar	Some dynamic creep characteristics of gypsum (M.S.). 2a(1), 2a(2)
132.	1962	F. H. K. Esser	A model study of the application of roof bolts under unsymmetrical loading conditions (M.S.). 3b
133.	1962	D. F. Haber	A study of the stress distribution around circular openings using multi-layered photoelastic material (M.S.). 1b, 3b
134.	1962	C. Haycocks	Mechanics of the Voussoir arch as applied to block caving (M.S.). 3b
135.	1963	A. J. Bush	Some effects of impact of low magnitude on the deformation of prestressed gypsum cylinder (M.S.). 2a(1)
136.	1963	A. H. Gomah	Application of photoelasticity to the stability of slopes in open-pit mines (M.S.). 1b, 3a
137.	1963	M. S. Oudenhoven	A model study of the behavior of elastic liners in shallow underground openings (M.S.). 1b, 3b
138.	1964	C. K. Quan	The characteristics of radial strain propagation induced by explosive impact in Jefferson City dolomite (M.S.). 1d, 2a(2)
139.	1965	H. Habenicht	A study of the influence of shock waves on the stability of rock bolt anchorage (M.S.). 1d, 3b

Doctoral Thesis

Department of Mining Engineering

140.	1964	G. B. Rupert	A study of plane and spherical compressional waves in a Voight visco-elastic medium (Ph.D.). 1d

MONTANA SCHOOL OF MINES

Master's Theses

Department of Mining Engineering

141.	1964	O. E. Oliveros	Plastic behavior of Torpedo sandstone under triaxial testing (M.S.). 2a(1)

142.	1965	W. J. Van Matre	Dynamic determination of elastic moduli of rock—an investigation (M.S.). 2a(2)

OHIO STATE UNIVERSITY*

Master's Theses

Department of Civil Engineering

143.	1954	R. R. Ryland	Relationship of thrust, torque, and rate of penetration in rotary drilling of brittle materials (M.S.). 2a(1), 3d(1)
144.	1957	C. A. Beasley	A fundamental study of internal pressure distribution in homogenous bulk solids (M.S.). 1b, 2a(1)
145.	1958	W. J. Verner	A fundamental study of internal vertical stress distribution in confined bulk solids (M.S.). 1b, 2a(1)
146.	1959	W. L. Nangle	A study of the internal stress distribution in a confined bulk solid (M.S.). 1b, 2a(1)
147.	1961	H. E. Rutherford	Evaluation of specific rock properties by ultrasonic principles (M.S.). 2a(1)
148.	1963	C. A. Willson	Laboratory procedures to determine fundamental rock properties that are critical in rock mechanics research (M.S.). 2a(1)

Doctoral Thesis

Department of Geology

149.	1965	C. E. Norman	Microfractures and residual stresses in rocks of several selected areas (tentative title—Ph.D. in progress). 1a, 3f

PENNSYLVANIA STATE UNIVERSITY*

Master's Theses

Department of Mining

150.	1958	O. Terichow	Efficiency measurements of roof bolt installations (M.S.). 3b
151.	1960	Y. C. Kim	A laboratory study in rock fragmentation in bench blasting (M.S.). 3d(2)
152.	1961	I. F. Jackson	A laboratory study of the machinability of slate (M.S.). 2a(1), 2a(2), 3c
153.	1962	T. Chao	Indexing relations in percussion drillings (M.S.). 3d(1)

154.	1963	J. C. Conway	An investigation of the stress distribution in a circular cylinder under static compressive load for varying boundary conditions (M.S.). 1b
155.	1964	R. de la Cruz	Efficiency of anchorage in roof bolting (M.S.). 3b
156.	1964	C. Haynes	Influence of velocity on impact failure (M.S.). 3d(1)

Doctoral Theses

Department of Mining

157.	1961	M. M. Singh	Mechanism of rock failure under impact of a chisel shaped bit (Ph.D.). 1c, 2a(1), 3[illegible]
158.	1961	R. Stefanko	Underground stress instrumentation and support evaluation (Ph.D.). 3b
159.	1962	S. Tandanand	Photoelastic investigation of failure phenomena in brittle media under concentrated loads (Ph.D.). 1c

QUEEN'S UNIVERSITY (Kingston, Ontario)

Master's Theses

Mining Engineering Department

160.	1958	C. L. Emery	The prestressed condition of the rocks around a mine opening (M.S.). 1b, 3b
161.	1962	R. L. Fowler	Investigation of some physical properties of rock from the Falconbridge mine (M.S.). 2a(1)
162.	1962	A. V. Pegler	The measurements of strains in rocks by photoelastic analysis (M.S.). 1b
163.	1962	J. D. Smith	The condition of stress surrounding a simulated mine opening (M.S.). 1b, 3b
164.	1963	R. S. Brittain	A quantitative study of deformation in thin specimens (M.S.). 1b
165.	1963	M. Rana	Experimental determination of viscosity of rocks (M.S.). 1b, 2a(1)
166.	1963	J. C. Wilson	Diamond drill core as an indicator of inherent strain in mine rocks (M.S.). 1b, 2a(1)

Doctoral Theses

Mining Engineering Department

167.	1965	A. V. Pegler	Study of fundamentals of rock fracture by hydraulic techniques (Ph.D. in progress). 1c, 2a(1)

168.	1965	M. Rana	Application of multiple-beam interferometry to study of inter- and intragranular deformation of rocks (Ph.D.). 1b

SOUTH DAKOTA SCHOOL OF MINES AND TECHNOLOGY

Master's Theses

Department of Mining Engineering

169.	1959	H. A. Kelly	Investigation of some physical and optical properties of stress-relieved rock specimens (M.S.). 2a(1)
170.	1962	S. D. Artus	An attempted correlation of the optical characteristics and mechanical properties of a part of the Poorman formation at Lead, South Dakota (M.S.). 2a(1)
171.	1963	L. A. Stinnett	An experimental approach to determining the influence of fabric and confining pressure on the mechanical properties of rocks (M.S.). 2a(1)
172.	1964	E. R. Hoskins	The development of an instrumentation system for measuring strain in rock (M.S.). 2a(1), 2a(2), 2b(1), 2b(2)
173.	1964	R. E. Johnson	An application of the theory of linear viscoelasticity to a circular mine shaft problem (M.S.). 1b, 1c, 3b

SOUTHERN CALIFORNIA, UNIVERSITY OF*

Master's Thesis

Department of Geology

174.	1965	H. Rieke	Rock mechanics studies of the Santa Monica slate, Santa Monica Mountains, Los Angeles County, California (M.S. in progress). 2a(1), 3a

STANFORD UNIVERSITY*

Master's Thesis

Department of Geophysics

175.	1964	L. J. Meister	Relationship between seismic velocity anisotropy and petrofabrics in Twin Sisters dunite (M.S.). 2a(2)

Doctoral Theses

Department of Geophysics

176.	1962	G. R. Fowles	Shock-wave compression of quartz (Ph.D.). 1d, 2a(2)

177.	1964	V. S. Tuman	Elastic energy propagation in medium under variable stresses (Ph.D.). 1d, 2a(2)
178.	1965	C. Young	The mechanical properties of some ultra-mafic minerals at elevated temperatures and pressures (Ph.D. in progress). 2a(1), 2a(2)

TEXAS, UNIVERSITY OF*

Master's Theses

Department of Petroleum Engineering

179.	1960	C. E. Nemir	The effect of particle size distribution on granular lost-circulation materials and on drilling mud filtration (M.S.). 2a(1), 3d(1)
180.	1960	Suttle, Jr.	The effect of regrinding of cuttings on drilling rate in rotary drilling (M.S.). 1b, 2a(1), 3d(1)
181.	1961	N. E. Garner	The photoelastic determination of the stress distribution caused by a bit tooth on an indexed surface (M.S.). 1b, 2a(1), 3d(1)
182.	1961	J. D. Ham	Mathematical study of the potential distribution ahead of the bit in rotary drilling (M.S.). 1b, 3d(1)
183.	1962	A. Diaz	Core permeability variations during the surge loss filtration period (M.S.). 1b, 2a(1), 3d(1)
184.	1962	J. W. Meyer	Photographic study of formation and ejection of cuttings in drag bit drilling (M.S.). 2a(1), 3d(1)
185.	1963	H. Crisp	Additional studies: fixed-blade planing of rock in the brittle stress state (M.S.). 1c, 2a(1), 3d(1)
186.	1963	F. S. Young, Jr.	Combination rolling cutter-drag bit studies (M.S.). 2a(1), 3d(1)
187.	1964	Y. Y. Youash	Dynamic physical properties of rocks (M.S.). 2a(2), 3d(1)
188.	1965	A. L. Podio	Effect of pore-fluid viscosity during single bit blow chisel impact (M. S.). 1b, 2a(1), 3d(1)
189.	1965	J. H. Yang	Impulsive loading by vertical impact of permeable rocks at elevated stress states (M.S.). 1b, 2a(1), 3d(1)

Doctoral Theses

Department of Civil Engineering

190.	1959	S. Serata	Development of design principles for disposal of reactor waste into underground salt cavities (Ph.D.). 3b
191.	1965	R. E. Smith	A lattice analogy for the solution of nonlinear stress problems (Ph.D.). 1b

Department of Geology

192.	1950	H. J. Jones	Experimental studies of the elasticity of rocks (Ph.D.). 2a(1)
193.	1965	Y. Y. Youash	Experimental deformation of layered rocks (Ph.D.). 2a(1)

Department of Petroleum Engineering

194.	1962	K. E. Gray	Fixed-blade planing of rocks in the brittle stress state (Ph.D.). 1c, 2a(1), 4d(1)
195.	1963	N. E. Garner	Experimental study of crater formation in rocks at elevated stress states (Ph.D.). 1c, 2a(1)
196.	1964	M. E. Chenevert	The deformation-failure characteristics of laminated sedimentary rocks (Ph.D.). 1b, 1c, 2a(1)

UTAH, UNIVERSITY OF*

Master's Theses

Department of Civil Engineering

197.	1960	T. N. Mutlo	Tunneling (M.S.). 3b
198.	1960	G. H. Turner	Projectile effects and subsurface disturbance in high-velocity-impact cratering in lead (M.S.). 1b, 1c
199.	1961	R. C. Kent	A strain gauge for use in drill holes (M.S.). 2a(1), 2a(2), 2b(1), 2b(2)
200.	1962	D. Metra	A bibliography on geomechanics (M.S.). 1, 2, 3
201.	1963	A. Afify	Ground movement and roof control in mining stratified deposits (M.S.). 3b
202.	1963	R. Hepworth	Heaving in Mancos shale (M.S.). 3a
203.	1963	W. Morn	Foundation conditions, Cart Creek Bridge, Daggett County, Utah (M.S.). 3a

Doctoral Thesis

Department of Civil Engineering

204.	1962	J. R. Hoskins	Design and construction of a basic geomechanics laboratory (Ph.D.). 2a(1)

VIRGINIA POLYTECHNIC INSTITUTE*

Master's Theses

Department of Mining Engineering

205.	1937	F. E. Watkins	Grindability of Virginia coals (M.S.). 3d(1)
206.	1948	R. W. Graham	Effect of coal grindability upon nozzle pulverization (M.S.). 3d(3)
207.	1956	F. L. Gaddy	A study of the ultimate strength of coal as related to the absolute size of the cubical samples tested (M.S.). 2a(1)
208.	1961	R. L. Dulaney	The structural strength of coal mine floors (M.S.). 2b
209.	1961	S. H. Pang	Factors affecting open-cut mining design (M.S.). 2a
210.	1962	J. M. Noble	The relationships between the crushing strength of brittle materials and the size of cubical specimens tested (M.S.). 2a(1)
211.	1962	H. Su	Some factors that affect a suspension-timbering design for underground roof control (M.S.). 3b

WISCONSIN, UNIVERSITY OF*

Master's Theses

Department of Mining Engineering

212.	1960	A. K. Mertdogan	Determination of practical solution to rock blasting (M.S.). 3d(1)
213.	1965	K. K. Wu	Investigation of physical properties of rock under impact, using relationship of rupturing force to hole diameter and burden (M.S.). 2a(1), 3d(2)

Doctoral Theses

Department of Mining Engineering

214.	1962	S. S. Salufa	Study of the mechanism of rock failure under the action of explosives (Ph.D.). 1c, 3d(2)
215.	1962	J. J. Scott	Three-dimensional photoelastic study of stress fields around room and pillar openings (Ph.D.). 1b, 3b

Appendix F

UNIVERSITY THESES AND GOVERNMENT PROJECTS CATEGORIZED BY SCOPE

Numbers refer to those assigned to theses in Appendix E and to government projects in Appendix I.

1. FUNDAMENTALS (Theory and model studies)

   a. State of stress in the earth's crust
      University theses: 15, 72, 87, 88, 149, 192.
      Government projects: 26, 34, 39, 69, 104, 107, 131, 166, 181, 182, 184.

   b. Stress-and-strain distribution
      University theses: 12, 16, 17, 18, 19, 21, 22, 25, 27, 29, 32, 35, 39, 40, 42, 43, 44, 52, 58, 59, 63, 64, 65, 68, 71, 75, 76, 78, 80, 82, 83, 85, 86, 99, 101, 108, 110, 111, 113, 128, 129, 133, 136, 137, 144, 145, 146, 154, 160, 162, 163, 164, 165, 166, 168, 173, 180, 181, 182, 183, 188, 189, 191, 196, 198, 200, 215.
      Government projects: 9, 19, 20, 22, 23, 24, 28, 31, 43, 61, 63, 64, 66, 73, 74, 76, 78, 79, 83, 97, 98, 99, 100, 105, 107, 110, 111, 113, 116, 128, 129, 137, 142, 143, 144, 151, 152, 163, 164, 166, 177, 178, 179, 180, 181, 182, 184, 185.

   c. Failure theory
      University theses: 2, 14, 16, 26, 35, 39, 40, 42, 43, 44, 49, 50, 53, 55, 58, 62, 63, 64, 65, 77, 78, 80, 81, 83, 85, 89, 93, 108, 111, 113, 129, 157, 159, 167, 173, 185, 194, 195, 196, 198, 200, 214.
      Government projects: 14, 15, 16, 20, 22, 23, 25, 28, 35, 38, 43, 50, 51, 60, 61, 63, 65, 73, 74, 76, 78, 83, 98, 99, 101, 104, 105, 107, 111, 113, 119, 121, 124, 125, 127, 128, 142, 143, 144, 145, 151, 152, 165, 171, 175, 177, 179, 180, 183, 185.

   d. Stress-wave theory
      University theses: 74, 82, 138, 139, 140, 176, 177, 192.
      Government projects: 8, 21, 27, 30, 33, 36, 37, 40, 41, 42, 43, 45, 46, 52, 54, 56, 67, 68, 72, 73, 74, 76, 101, 103, 104, 121, 122, 123, 159, 165.

2. MEASUREMENTS

a. Laboratory

(1) Static

University theses: 5, 6, 7, 10, 11, 14, 16, 17, 18, 28, 30, 31, 34, 36, 37, 38, 42, 43, 44, 46, 48, 49, 55, 56, 57, 60, 61, 62, 63, 64, 65, 66, 67, 69, 70, 73, 78, 79, 81, 84, 90, 91, 92, 93, 95, 96, 97, 98, 103, 104, 105, 109, 115, 118, 119, 121, 122, 126, 127, 130, 131, 134, 141, 143, 144, 145, 146, 147, 148, 152, 157, 161, 165, 166, 167, 169, 170, 171, 172, 174, 178, 179, 180, 181, 183, 184, 185, 186, 188, 189, 192, 193, 196, 199, 200, 204, 207, 210, 213.

Government projects: 1, 6, 7, 13, 24, 29, 31, 32, 35, 38, 47, 48, 49, 52, 55, 60, 62, 63, 64, 67, 68, 70, 78, 98, 99, 102, 105, 112, 118, 119, 120, 133, 135, 138, 139, 131, 142, 143, 148, 150, 153, 160, 168, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 183.

(2) Dynamic

University theses: 3, 4, 6, 8, 9, 11, 13, 36, 52, 53, 78, 79, 90, 91, 97, 107, 112, 120, 131, 138, 142, 152, 172, 175, 176, 177, 178, 187, 195, 199, 200.

Government projects: 3, 5, 7, 17, 18, 30, 33, 34, 47, 48, 49, 50, 56, 62, 96, 102, 112, 118, 133, 135, 136, 139, 148, 151, 152, 154, 155, 159, 167, 169, 172, 185.

b. Field

(1) Static

University theses: 6, 45, 57, 62, 78, 172, 191, 192.

Government projects: 1, 2, 19, 29, 57, 58, 69, 70, 81, 87, 88, 89, 90, 91, 92, 102, 105, 108, 109, 110, 112, 114, 132, 135, 137, 139, 140, 164.

(2) Dynamic

University theses: 6, 8, 45, 78, 102, 172, 191, 192.

Government projects: 8, 9, 11, 16, 19, 26, 27, 36, 37, 43, 54, 81, 87, 88, 89, 90, 91, 92, 95, 102, 103, 112, 122, 133, 135, 136, 137, 139, 140, 185.

3. APPLICATIONS

a. Surface foundations, surface excavations, and natural slopes

University theses: 24, 79, 81, 136, 174, 200, 202, 203, 209.

Government projects: 4, 9, 10, 11, 12, 14, 15, 65, 75, 82, 84, 85, 86, 87, 88, 89, 90, 91, 92, 94, 109, 115, 117, 137.

b. Underground openings (including boreholes)

University theses: 12, 24, 41, 47, 50, 55, 59, 62, 71, 78, 79, 83, 85, 86, 90, 91, 92, 94, 99, 106, 108, 110, 116, 128, 130, 132, 133, 134, 137, 139, 150, 155, 158, 160, 163, 173, 190, 197, 200, 201, 208, 211, 215.

Government projects: 2, 9, 46, 49, 58, 64, 71, 77, 80, 82, 83, 87, 88, 89, 90, 91, 92, 94, 106, 107, 111, 129, 130, 135, 140, 145, 149.

c. Rock as a construction material

University theses: 152, 192.

Government projects: 93.

d. Comminution

(1) Drilling

University theses: 33, 34, 51, 54, 56, 117, 118, 119, 120, 121, 122, 123, 143, 153, 156, 157, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 194, 200.

Government projects: 57, 59, 124, 125, 126, 127, 128, 134, 180.

(2) Blasting

University theses: 51, 54, 100, 124, 151, 200, 212, 213, 214.

Government projects: 10, 43, 44, 101, 103, 104, 121, 122, 123, 135, 150.

(3) Crushing

University theses: 200, 205, 206.

Government projects: none.

e. Subsidence

University theses: 20, 23, 45, 125, 200.

Government projects: 106, 147.

f. Structural geology

University theses: 1, 58, 87, 114, 149, 200.

Government projects: 16, 26, 36, 100, 109, 114, 123, 130, 146, 156, 157, 158, 159, 161, 162, 163, 164.

Appendix G

SAMPLE QUESTIONNAIRE SENT TO INDUSTRY

Page 1

INDUSTRY SURVEY OF RESEARCH IN ROCK MECHANICS

1. Are you or your organization doing research in Rock Mechanics or in related fields? (If "yes," please describe your work briefly.)

Yes ( ) No ( )

2. If your policy permits, kindly give estimates of total annual cost of your research.

CALENDAR	ROCK MECHANICS	RELATED RESEARCH
1963		
1964		
1965		

3. If not currently engaged in such research, are you planning any for the future?

Yes ( ) No ( )

(OVER)

Page 2

4. Do you or your organization support or have plans to support research in rock mechanics as a non-commercial venture (such as by university fellowships)?

Yes ( ) No ( )

5. If your answer to 4 is "yes," please describe and, if in accord with your policy, please give cost estimates.

6. Would you like to continue receiving information on the work of the Committee on Rock Mechanics?

Yes ( ) No ( )

Appendix H

COMPANIES RESPONDING TO QUESTIONNAIRE AND COMPANIES SUPPORTING THE COMMITTEE

*Companies reporting rock-mechanics research.
†Companies supporting Committee's activities with a contribution.

CONSULTING AND CONTRACTING
- T. F. Adams, Denver, Colo.
- American Mining Congress, Washington, D.C.
- Atlantic, Gulf & Pacific Co., New York, N.Y.
- Baker, Michael, Jr., Inc., Rochester, Pa.*†
- Behre Dolbear & Company, Inc., New York, N.Y.*
- Bituminous Coal Operators' Association, Washington, D.C.
- California Research Corporation, San Francisco, Calif.†
- Converse Foundation Engineers, Pasadena, Calif.*
- Core Laboratories, Inc., Dallas, Tex.*
- Dames & Moore, Los Angeles, Calif.†
- Elio D'Appolonia, Pittsburgh, Pa.†
- Douglas Aircraft Company, Inc., Santa Monica, Calif.*
- Dravo Corporation, Pittsburgh, Pa.*
- Fenix and Scisson, Inc., Tulsa, Okla.
- Galigher Company, The, Salt Lake City, Utah
- Halliburton Company, Duncan, Okla.*†
- Harza Engineering Company, Chicago, Ill.†
- Holmes & Narver, Inc., Los Angeles, Calif.*†
- IIT Research Institute, Chicago, Ill.*
- Isbell Construction Co., Reno, Nev.
- Al Johnson Construction Co., Minneapolis, Minn.†
- Peter Kiewit Sons' Co., Omaha, Neb.
- Leeds, Hill and Jewett, Inc., San Francisco, Calif.†
- Arthur D. Little, Inc., Cambridge, Mass.*
- Mackintosh & Mackintosh, Inc., Los Angeles, Calif.
- Marquardt Corporation, The, Van Nuys, Calif.*
- Parsons, Brinckerhoff, Quade & Douglas, New York, N.Y.†
- Lucius Pitkin, Inc., New York, N.Y.*†
- Raymond International Inc., New York, N.Y.
- Sandia Corporation, Albuquerque, N.M.*
- Schlumberger Well Surveying Corporation, Houston, Tex.*†

Shannon & Wilson, Inc., Seattle, Wash.*
Soil Mechanics and Foundation Engineers, Inc., Sunnyvale, Calif.*†
United Electrodynamics, Inc., Pasadena, Calif.*
United Geophysical, Pasadena, Calif.*
Vibration Measurement Engineers, Evanston, Ill.*
Walsh Construction Company, San Mateo, Calif.
Woodward, Clyde, Sherard & Associates, Oakland, Calif.†

MANUFACTURING

Acker Drill Company, Inc., Scranton, Pa.*†
Alkirk Corporation, Seattle, Wash.*
Allied Chemical Corporation, New York, N.Y.†
Allis-Chalmers Manufacturing Company, Milwaukee, Wis.*
American Cyanamid Company, Wayne, N.J.*
Atlas Chemical Industries, Inc., Wilmington, Del.
Blue Diamond Company, Los Angeles, Calif.*
Boeing Company, The, Seattle, Wash.
Boyles Bros. Drilling Co., Salt Lake City, Utah†
Caterpillar Tractor Co., Peoria, Ill.†
Dresser Industries, Inc., Dallas, Tex.*
E. I. du Pont de Nemours & Company, Wilmington, Del.
Gardner-Denver Company, Denver, Colo.*
Hercules Powder Company, Inc., Wilmington, Del.†
Hughes Tool Company, Houston, Tex.*†
Ingersoll-Rand Co., Bedminster, N.J.*
International Harvester Company, Melrose Park, Ill.*
Jones & Laughlin Steel Corporation, Pittsburgh, Pa.†
Le Roi Division, Westinghouse Air Brake Company, Sidney, Ohio*
E. J. Longyear Company, Minneapolis, Minn.
Mission Manufacturing Company, Houston, Tex.*
North American Aviation, Inc., El Segundo, Calif.
Northrop Aviation Company, Hawthorne, Calif.
Reed Roller Bit Corporation, Houston, Tex.*
Riverside Cement Co., Los Angeles, Calif.†
Soiltest, Inc., Evanston, Ill.*
W. F. Sprengnether Instrument Co., Inc., St. Louis, Mo.
Structural Behavior Engineering Laboratories, Phoenix, Ariz.*

MINING

Allied Chemical Corporation, Syracuse, N.Y.
American Cement Corporation, Los Angeles, Calif.
American Metal Climax, Inc., New York, N.Y.*†
American Smelting & Refining Company, New York, N.Y.†
American Zinc Co. of Tennessee, Mascot, Tenn.*
Armour and Company, Chicago, Ill.
Atchison, Topeka and Santa Fe Railway System, The, Chicago, Ill.
Atlas Minerals, Salt Lake City, Utah
Bagdad Copper Corp., Shaker Heights, Ohio
Banner Mining Corp., Tucson, Ariz.
Basic, Incorporated, Cleveland, Ohio†
Bethlehem Steel Corporation, Bethlehem, Pa.*†
Calumet & Hecla, Inc., Calumet, Mich.*
Cerro Corporation, New York, N.Y.†
Cleveland-Cliffs Iron Co., The, Ishpeming, Mich.*†

Climax Molybdenum Company, Climax, Colo.*†
Colorado Fuel & Iron Corporation, The, Pueblo, Colo.
Consolidation Coal Company, Pittsburgh, Pa.
Copper Range Company, New York, N.Y.†
Cyprus Mines Corporation, Los Angeles, Calif.†
Diamond Crystal Salt Company, St. Clair, Mich.*
Dow Chemical Company, The, Midland, Mich.*
Duvall Corporation, Carlsbad, N.M.
Eagle-Pitcher Company, The, Miami, Okla.
FMC Corporation, Green River, Wyo.*
Freeport Sulphur Company, New York, N.Y.†
General Refractories Co., Philadelphia, Pa.
Glen Alden Coal Company, Wilkes-Barre, Pa.
Hanna Mining Company, The, Cleveland, Ohio†
Hecla Mining Co., Wallace, Ida.*†
Homestake Mining Company, San Francisco, Calif.
Idarado Mining Company, Ouray, Colo.
Inland Steel Company, East Chicago, Ind.*
Inspiration Consolidated Copper Co., Inspiration, Ariz.
Kaiser Aluminum & Chemical Corporation, Oakland, Calif.
Kaiser Steel Co., Sunnyside, Utah
Kennecott Copper Corp., Salt Lake City, Utah†
Lowphos Ore, Limited, Capreol, Ont., Canada*
Magma Copper Company, Superior, Ariz.*
Marcona Mining Company, Lima, Peru
Monsanto Company, St. Louis, Mo.
National Lead Company, New York, N.Y.†
New Jersey Zinc Company, The, New York, N.Y.
Newmont Mining Corporation, New York, N.Y.†
North Range Mining Company, Negaunee, Mich.
Oglebay Norton Company, Cleveland, Ohio†
Peabody Coal Company, St. Louis, Mo.
Phelps Dodge Corp., New York, N.Y.†
Pickands Mather & Co., Cleveland, Minn.
Pittsburgh Plate Glass Company, Pittsburgh, Pa.*†
Potash Co. of America, Carlsbad, N.M.
Republic Steel Corporation, Cleveland, Ohio†
Reserve Mining Co., Silver Bay, Minn.†
St. Joseph Lead Company, Bonne Terre, Mo.*†
J. R. Simplot Company, Boise, Ida.
Southwest Potash Corporation, New York, N.Y.*
Stauffer Chemical Co., San Francisco, Calif.*
Sunshine Mining Company, Kellogg, Ida.
Tennessee Copper Company, Copperhill, Tenn.*
Texas Gulf Sulphur Company, New York, N.Y.*
Union Carbide Corporation, New York, N.Y.†
U.S. Borax, Los Angeles, Calif.
United States Gypsum Company, Chicago, Ill.
U.S. Smelting, Refining, and Mining Co., Salt Lake City, Utah
United States Steel Corporation, Pittsburgh, Pa.*†
Utah Construction & Mining Co., San Francisco, Calif.†
Vanadium Corporation of America, Cambridge, Ohio
White Pine Copper Company, White Pine, Mich.*
Wyandotte Chemicals Corporation, Wyandotte, Mich.*

PETROLEUM

Atlantic Refining Company, The, Dallas, Tex.*†
California Oil Company, Perth Amboy, N.J.
Cities Service Oil Company, Bartlesville, Okla.*†
El Paso Natural Gas Co., El Paso, Tex.
ESSO Production Research Company, Houston, Tex.*
Gulf Research & Development Company, Pittsburgh, Pa.*†
Humble Oil & Refining Co., Houston, Tex.†
Marathon Oil Co., Littleton, Colo.
Pan American Petroleum Corporation, Tulsa, Okla.*†
Phillips Petroleum Company, Bartlesville, Okla.*
Pure Oil Company, The, Crystal Lake, Ill.
Shell Development Company, Houston, Tex.*†
Sinclair Oil & Gas Co., Tulsa, Okla.
Socony Mobil Oil Company, Inc., Dallas, Tex.*†
Standard Oil Co. (Ohio), Cleveland, Ohio
Texaco, Incorporated, Bellaire, Tex.*
Union Oil Company of California, Brea, Calif.*

Appendix I

GOVERNMENT RESEARCH PROJECTS IN ROCK MECHANICS, 1963 TO 1966

Code following data corresponds to paragraphing in tabular material on p. 4.

ATOMIC ENERGY COMMISSION, U.S.

1. Laboratory and field methods of measurement of creep in rock salt in response to radiogenic heat, Oak Ridge National Laboratory (ORNL) 2a(1), 2b(1)
2. Field measurements of the uplift and stress distribution in shale resulting from fractures induced by grout injection, ORNL 2b(1), 3b
3. Determination of the equation of state of oil shale both parallel and normal to stratification, Sandia Corporation 2a(2)
4. Mechanics of rock slides simulated in the laboratory with granular materials: slide shape as a function of mass of material, flow rate, height of fall, material density, and angularity of particles, Sandia Corporation 3a
5. Hydrodynamic equation of state of rocks at very high pressures and the behavior of rocks in the nonelastic region, Sandia Corporation 2a(2)
6. Static strength, elastic properties, porosity, density, permeability, and petrographic description of selected rocks, Department of Mineral Technology, University of California; Lawrence Radiation Laboratory; Corps of Engineers Waterways Experiment Station 2a(2)
7. Compressibility, equation of state, thermoconductivity, dynamic elastic limits, and description of plastic yield, Lawrence Radiation Laboratory 2a(2), 2a(2)
8. Attenuation of sonic velocity of rocks in situ by fractures, U.S. Geological Survey 1d, 2b(2)
9. Research on in situ response of rocks to nuclear explosions such as cavity growth, chimney and spalling dimensions, cracking radius, ground motion propagation, possibility of damage to slopes, and underground openings, R. F. Beers, Inc. 1b, 2b(2), 3a, 3b

DEPARTMENT OF COMMERCE

Bureau of Public Roads

10. Presplitting techniques in rock excavation, Alabama State Highway Department: $5,000 3a, 3d(2)

11. Monitoring subaudible rock noise and its application to highway stability problems, California State Highway Department: $21,000 2b(2), 3a

12. Rebound of materials in highway cuts (Ridge Route formation shale), California State Highway Department: $80,350 3a

13. Lithified shales in highway construction, Montana State Highway Department and Montana School of Mines: $40,500 2a(1)

14. Landslide research, Montana State Highway Department: $40,000 through 1966 1c, 3a

15. Study of landslides in South Dakota, South Dakota Highway Department and the South Dakota State Geological Survey: $68,885 1c, 3a

DEPARTMENT OF DEFENSE

Air Force

Office of Aerospace Research

16. S wave project for focal mechanism studies, W. V. Stauder, St. Louis University 1c, 2b(2), 3f

17. Research in dynamic compression of solids (irregular), Stanford Research Institute, Menlo Park: Office of Scientific Research (OSR) 2a(2)

18. Dynamic properties of rocks, Stanford Research Institute, Menlo Park; Air Force Office of Scientific Research, Advanced Research Projects Agency cosponsored with Cambridge Research Laboratories (CRL) 2a(2)

19. Earth deformation from nuclear detonation in salt, Stanford Research Institute: Office of Scientific Research, Plowshare Division of the U.S. Atomic Energy Commission (AEC) 1b, 2b(1), 2b(2)

20. Theoretical aspects of rock behavior under stress, Stanford Research Institute: OSR 1b, 1c

21. Studies in axially symmetric wave propagation problems in plastic and hydro-dynamic media, Stanford Research Institute: OSR 1d

22. Basic problems in dislocation theory, Columbia University: OSR 1b, 1c

23. Studies in the theory of a dislocated continuum, George Washington University: OSR 1b, 1c

24. Studies in viscoelastic media, California Institute of Technology: OSR 1b, 2a(1)

25. Research in mechanics of crack initiation and crack propagation, California Institute of Technology: OSR 1c

26. A specialized type of seismic research, A. E. Scheideger, University of Illinois 1a, 2b(2), 3f

27. Theoretical and field studies of seismic waves, J. Berg, Jr., Oregon State University 1d, 2b(2)

28. Investigations on the non-elastic behavior of the upper mantle, S. Mueller, Geophysical Institute of Technical University, Karlsruhe, Germany 1b, 1c

29. Ice and snow physics, Massachusetts Institute of Technology: CRL 2a(1), 2b(1)

30. Surface waves from couples, Terrestrial Sciences Laboratory: CRL 1d, 2a(2)
31. Shear deformation of rocks, Terrestrial Sciences Laboratory: CRL 1b, 2a(1)
32. Application of induction heating to rock deformation apparatus, Terrestrial Sciences Laboratory: CRL 2a(1)
33. Nature of surface wave propagation in crystal structure of varying thickness, L. Knopoff, University of California (Los Angeles) 1d, 2a(2)
34. Measurement of p and s sound velocities under pressure on laboratory models of the earth's mantle, O. L. Anderson, Columbia University 1a, 2a(2)
35. Research directed toward an electron microscope and x-ray analysis of deformed mineral specimens, B. S. LeMent, Man Laboratories, Inc. 1c, 2a(1)
36. Theoretical and model studies of seismic wave propagation in the presence of crustal discontinuities, J. Kane, University of Rhode Island 1d, 2b(2), 3f
37. Research on seismic waves generated by explosives in a multilayered medium, C. Kisslinger, St. Louis University 1d, 2b(2)
38. Rock failure in torsion tests, J. Handin, Shell Development Co. 1c, 2a(1)
39. Basic research in crustal studies, M. Backers, Texas Instruments 1a
40. Theoretical seismology, C. L. Pekeris, Weizmann Institute, Israel 1d

Weapons Laboratory

41. Scattering of transient elastic waves by a circular cavity, National Engineering Science Corp., 1964 1d
42. Study of the parameters which affect sealing of underground structures, General American Transportation Co., 1964 1d
43. Close-in effects from nuclear explosives, Armour Research Foundation, 1963 1b, 1c, 1d, 2b(2), 3d(2)
44. Experimental study of the effect of material properties on coupling of explosive energy, United Research Services, 1963 3d(2)
45. Interaction of plane elastic waves with a cylindrical cavity, University of Illinois, 1963 1d
46. Use of models to simulate dynamically loaded underground structures, Iowa State University and American Machine and Foundry Co. 1d, 3b
47. Studies of physical properties of rock which affect its behavior under dynamic loads, Oshier, South Dakota School of Mines and Technology, 1963: $52,068; 1964: $1,310 2a(1), 2a(2)
48. Study of behavior of soil and rock subjected to high levels of pressure and temperature, Kane, University of Illinois: $50,000 2a(1), 2a(2)
49. Development of indices relating the physical properties and the engineering behavior of rock, Deere, University of Illinois: $33,206 2a(1), 2a(2), 3b
50. Investigation of dynamic fracture of brittle materials, Martin, Melpar: $30,000 1c, 2a(2)
51. Resistance encountered in movement of rock masses along existing discontinuities, Withers and Deere, University of Illinois: $1,537 1c

52. Energy coupling and attenuation in rock, Coates, Canadian Bureau of Mines: $31, 484 1d

53. Behavior of soil and rock under high pressure, Comish, Illinois Institute of Technology and Research, Inc.: $38,650 2a(1)

54. Development of controlled impulse techniques for in situ testing of rock, Merrill, Bureau of Mines: $35,000 1d, 2b(2)

55. Behavior of rocks in one-dimensional static compression, Brown, University of Utah: $37,727 2a(1)

56. Shock unloading characteristics of crushable and porous rocks, Wiedermann, Illinois Institute of Technology and Research, Inc., 1963: $52,300; 1964: $93,554 1d, 2a(2)

Army, U.S.

Cold Regions Research and Engineering Laboratory

57. Related drilling and pile driving efforts in permafrost, Alaskan Department of Highways and U.S. Army Alaska District, 1950-1966 2b(1), 3d(1)

58. Permafrost tunnel, Fox, Alaska, 1962-1965 2b(1), 3b

59. Jet burners, Antarctic Studies, 1962-1966 3d(1)

60. Laboratory study of fundamental mechanics of cutters in frozen soils, 1966 1c, 2a(1)

61. Brittle fracture in frozen soils, 1966 1b, 1c

62. Visco-elastic properties of frozen soils, H. Stevens, F. Sayles, Experimental Engineering Division, 1966 2a(1), 2a(2)

63. Mechanics of ice, G. Frankenstein, Experimental Engineering Division, 1966 1b, 1c, 2a(1)

64. Rapid tunneling techniques in frozen ground, G. Swinzow, Experimental Engineering Division, 1966 1b, 2a(1), 3b

65. Excavation in frozen ground, G. Lange, Experimental Engineering Division, 1966 1c, 3a

66. Study of lateral and vertical snow pressure relationships, Experimental Engineering Division, 1966 1b

67. Thermophysical properties and flow characteristics of porous media, Y. Yen, Research Division, 1966 1d, 2a(1)

68. Geophysical properties of frozen material, Research Division, 1966 1d, 2a(1)

69. Surface movement studies on the Greenland ice cap, S. Moe, Research Division, 1966 1a, 2b(1)

Corps of Engineers

70. Evaluation of rock mass properties and correlation of laboratory and field data, Waterways Experiment Station (WES), 1966: $30,000 2a(1), 2b(1)

71. The static and dynamic stability of openings in rock masses, University of Illinois, WES, 1965 and prior: $50,000; 1966: $40,000 3b

72. Free-field wave propagation in a jointed rock mass, WES, 1966: $20,000 1d

73. Modeling the response of rock formations and inclusions to shock loadings, WES, 1965 and prior: $50,000; 1966: $90,000 1b, 1c, 1d

74. Static and dynamic strength and stress-strain characteristics of rock, WES, 1966: $40,000 1b, 1c, 1d

75. Examine slope failure, Massachusetts Institute of Technology, WES, 1965: $50,000 3a

76. Crater formation theory, Georgia Institute of Technology and Duke University, WES, 1965 and prior: $40,000 1b, 1c, 1d

77. Feasibility of constructing large underground cavities, WES (TR 3-648), July 1964 3b

78. Critical normal fracture stress, Ohio River District Laboratory (ORDL) 1b, 1c, 2a(1)

79. 3-D photoelastic stress, ORDL, 1966: $15,000 1b

80. Rock bolting (theory and evaluation), Missouri River District (MRD), 1965 and prior: $62,000; 1966: $30,000 3b

81. In situ test methods, University of Minnesota, MRD, 1966: $20,000 2b(1), 2b(2)

82. Rock mechanics investigations (rational design strength), MRD 1966: $20,000 3a, 3b

83. Circular arc stability analysis by computer, Nuclear Cratering Group (NCG) 1b, 1c, 3b

84. Geomechanical methods of nuclear crater slope stability, NCG 3a

85. High rock slope study (case histories), NCG and WES, 1965-1966 3a

86. Slope stability analysis for nuclear crater slopes, NCG and WES 3a

87. Field investigations on craters, SEDAN (PNE 234F), NCG, 1965 and prior: $126,000 2b(1), 2b(2), 3a, 3b

88. Field investigations on craters, DANNY BOY (PNE; Draft), NCG, 1965 and prior: $98,000 2b(1), 2b(2), 3a, 3b

89. Field investigations on craters, SULKY (PNE 719F), NCG, 1965 and prior: $45,000 2b(1), 2b(2), 3a, 3b

90. Field investigations on craters, Pre-SCHOONER (PNE 505F), NCG, 1965 and prior: $177,000 2b(1), 2b(2), 3a, 3b

91. Field investigations on craters, DUGOUT (PNE 602F), NCG, 1965 and prior: $119,000 2b(1), 2b(2), 3a, 3b

92. Field investigations on craters, Pre-SCHOONER II, NCG, 1966: $74,000 2b(1), 2b(2), 3a, 3b

93. Manufacture of riprap and aggregate by nuclear methods (PNE 5003), NCG, 1965 and prior: $30,000 3c

Office of Civil Defense

94. Blast shelter siting study, Stanford Research Institute: $75,000 3a, 3b

Office of Research and Development

95. Ultrasonic model study of elastic waves in layered media, F. Press, California Institute of Technology 2b(2)

96. Experiments on measurements of response of rock to dynamic loads, Missouri School of Mines 2a(2)

97. Stress-strain instrumentation for rock and soil, Atlantic Research Corporation 2b

Navy

Naval Weapons Laboratory

98. Some dynamic characteristics of rocks, Naval Ordnance Test Station 2a(2)

Office of Naval Research

99. Mechanical properties of rocks at high temperatures and pressures, W. Elsevier, Princeton University 1b, 1c, 2a(1)

100. Plastic flow of rock at high temperatures and pressures, R. B. Gordan, Yale University 1b, 1c, 2a(1)

101. An evaluation of the application of semi-conductor strain gages to the study of internal strain in bedrock consequent to earthquakes, Rev. D. Lineham, Boston College 1b, 3f

DEPARTMENT OF INTERIOR

Bureau of Mines

Application of Physics to Mining, College Park, Maryland

102. Fundamental blasting studies 1c, 1d, 3d(2)

103. Dynamic rock mechanics (dynamic physical properties of rock up to intermediate, dynamic pressures) 2a(1), 2a(2), 2b(1), 2b(2)

104. Vibrations from quarry blasting and their effect on structures 1d, 2b(2), 3d(2)

105. Mechanics of pre-splitting 1a, 1c, 1d, 3d(2)

106. Deformation versus applied stress on evaporite minerals (in situ and laboratory investigation) 1b, 1c, 2a(1), 2b(1)

107. Rock mechanics of block caving–instruments and subsidence (laboratory investigation) 3b, 3c

108. Rock burst–stress and failure conditions, etc. 1a, 1b, 1c, 3b

Mining Engineering, Applied Rock Mechanics, Physical Properties–Hand Specimen Size and Larger, Slope Stability, Denver, Colorado and Reno, Nevada

109. Open pit design, full scale experiment 3a, 2b(1)

110. Physics of earth structure: (a) In place physical properties, (b) Structural studies 2b(1), 3f

111. Stress concentrations below undercuts 1b, 2b(1)

112. Pillar robbing 1b, 1c, 3b

113. Instrumentation 2a(1), 2a(2), 2b(1), 2b(2)

114. Stress and deformation beyond elastic limit 1b, 1c

115. Structural studies (in situ physical properties) 2b(1), 3f

116. Example rock slopes 3a

117. Stress analyses of open pits 1b

118. Slope strength and forewarning devices 3a

Dynamics and Small Scale Properties, Minneapolis, Minnesota

119. Fundamental rock studies 2a(1), 2a(2)

120. Anisotropism versus strength 1c, 2a(1)

121. Effect of environment upon physical properties (heat) 2a(1)

122. Blasting model studies 1c, 1d, 3d(2)

123. Seismic effect of underground blasting 1d, 2b(2), 3d(2)

124. Effect of geologic structure on blasting 1d, 3d(2), 3f

125. Thermal fragmentation 1c, 3d(1)

126. Rock fragmentation by dielectric and indirection heating 1c, 3d(1)

127. Effect of chemical additives on rock fragmentation 3d(1)

128. Rock fragmentation by electro-hydraulics 1c, 3d(1)

129. Fundamental drilling studies 1b, 1c, 3d(1)

Artificial Support and Rock Burst, Spokane, Washington

130. Rock behavior in relation to artificial support loading and design 1b, 3b

131. Rock behavior in relation to artificial support loading and design (rock structure interpretation) 3f

132. Rock behavior in relation to artificial support loading and design (lithostatic pressure) 1a

133. Underground straining frame 2b(1), 3b

Bureau of Reclamation

134. Determination of physical and mechanical properties and petrographic features of prevalent foundation rock types 2a(1), 2a(2), 2b(2)

135. Development of drill performance monitor to provide a continuous record of physical conditions, such as rate of advance, at the drill face 3d(1)

136. Investigation of the engineering behavior of rockfill and rock formations at underground powerplant and tunnel sites, correlations of test results obtained during field and laboratory tests of foundation rock, and studies of rock bolts, rock bolting, and underground blasting techniques 2a(1), 2a(2), 2b(1), 2b(2), 3b, 3d(2)

137. Ultrasonic testing to provide instantaneous indications of modulus of elasticity of rock samples under both field and laboratory conditions 2a(2), 2b(2)

138. Development of improved equipment and methods for conducting site tests to determine the structural properties of rock foundations and the stress fields which exist therein 1b, 2b(1), 2b(2), 3a

139. Study of basic properties of rock-forming minerals to establish relationships between engineering properties and petrographic characteristics of these minerals 2a(1)

140. Instrumentation for rock mechanics measurements 2a(1), 2a(2), 2b(1), 2b(2)

141. Development of seismitron and gravimeter applications which will aid in design and construction of underground openings 2b(1), 2b(2), 3b

142. Creep and solubility study of gypsum and limestone 2a(1)

Geological Survey

Theoretical Geophysics Branch—Experimental Geology

143. Rock deformation (No. 7340), E. C. Robertson 1b, 1c, 2a(1)

144. Elastic and anelastic properties (No. 7344), L. Peselnick 1b, 1c, 2a(1)

Engineering Geology Branch—Engineering Geology

145. Deformation research (theoretical studies) (No. 9752), S. P. Kanizay 1b, 1c

146. Cool mine bumps, Utah (No. 9753), F. W. Osterwald 1c, 3b

147. Straight Creek tunnel, Colorado (No. 9759), C. S. Robinson 3f

148. Ground movement inventory (No. 9760), A. S. Allen 3e

Special Projects Branch–Engineering Geology

149. Special topical studies (laboratory studies on physical properties) (No. 9516), J. H. Scott 2a(1), 2a(2)

150. Geologic studies, underground nuclear explosion in salt, New Mexico (No. 9521), L. M. Gard 3b

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

151. Multidisciplinary research leading to utilization of extraterrestrial resources (extension of the Bureau of Mines Program on Rock Physics and Fragmentation to include the Lunar Environment), $100,000 2a(1), 3d(2)

152. Effects of impact shock on rock and minerals, Ames Research Center: $160,000 1b, 1c, 2a(2)

153. Study of impact characteristics of selected non-metallic materials in a vacuum environment, Marshall Space Flight Center: $30,000 1b, 1c, 2a(2)

154. Experimental study of the effects of vacuum conditioning on the physical properties of selected materials, Marshall Space Flight Center: $75,000 2a(1)

155. Dynamic behavior of lunar surface materials, Langley Research Center: $100,000 2a(2)

156. Light vertical gas gun range (hypervelocity impacting of rocks), Ames Research Center: $40,000 2a(2)

157. Structural and mineralogical study of meteorite impact craters, Pennsylvania State University: $31,000 3f

158. Study of Wells Creek Basin, Tennessee, meteorite impact structure, Vanderbilt University: $32,000 3f

159. Petrographic study of West Hawk Lake structure, Manitoba, University of Houston: $8,000 3f

160. Broad study of lunar geology, including studies of: Meteor Crater, Arizona; Flynn Creek, Tennessee; Sierra Madera, Texas; Odessa Craters, Texas; Laboratory studies of shock equations of state; and mineralogic effects of shock, U.S. Geological Survey: $75,000 1d, 2a(2), 3f

161. Mechanical properties in lunar materials in _in situ_ conditions, Marshall Space Flight Center: $200,000 2a(1)

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162. Intensive study of San Andreas Fault (P-17071), Allen, California Institute of Technology: $242,000 (3 years) 3f

163. Q in the crust and top of the mantle (P-16870), Tuve, Carnegie Institution of Washington: $76,400 (2 years) 3f

164. Earth deformation in tectonically inactive area (P-17436), Kuo, Columbia University: $99,200 (5 years) 1b, 3f

165. Measurement of the response of the earth's crust to surface loading (GP-1335), Hales, Graduate Research Center of the Southwest: $56,000 (2 years) 1b, 2b(1), 3f

166. Role of stress waves in fracturing of rock (P-11474), Rinehart, Colorado School of Mines: $36,800 (2 years) 1c, 1d

167. Stress fields in underground formation (P-15360), Serata, Michigan State University: $61,800 (2 years) 1a, 1b

168. Relationship between fabric and compressional wave velocity in dunite (P-16420), Ragan, University of Alaska: $28,700 (2 years) 2a(2)

169. High pressure-temperature compressibility measurements by X-ray techniques (P-16491), Bassett and Takahashi, University of Rochester: $32,300 2a(1)

170. Rapidly running transitions at very high temperatures (GP-1339), Adams and Kennedy, University of California (Berkeley): $20,000 2a(2)

171. High temperature and high pressure in solid state geophysics (GP-1443), Newton, University of Chicago: $40,000 (3 years) 2a(1)

172. A theoretical and experimental study of brittle behavior of rocks (GP-1470), Brace, Massachusetts Institute of Technology: $90,000 (3 years) 1c, 2a(1)

173. Temperature dependence of the elastic constants of rock forming minerals (GP-1004), Simmons, Southern Methodist University: $27,600 (2 years) 2a(1), 2a(2)

174. The elasticity and density of the high-pressure polymorphs of selected solids (GP-980), Katz, Rensselaer Polytechnic Institute: $61,000 (2 years) 2a(1)

175. Limits to the mineralogical constitution of the upper mantle as deduced from high pressure experimental investigations (GP-1545), Clark, Yale University: $100,000 (3 years) 2a(1)

176. Brittle fracture of rocks (GP-282), Brace, Massachusetts Institute of Technology: $18,500 1c, 2a(1)

177. Phase equilibrium studies on a simplified eclogite system (GP-1218), Hamilton and Brunham, Pennsylvania State University: $50,000 (2 years) 2a(1)

178. Physical behavior of solids under very high pressures, J. C. Jamieson, University of Chicago 1b, 1c, 2a(1)

179. Mechanical anisotropy of solids during deformation, Gernard Oartel, University of California 1b, 2a(1)

180. Behavior of rock under stress (G-21391, P-9476), C. Fairhurst, University of Minnesota: $30,000 (2 years) 1b, 1c, 2a(1)

181. Mechanics of rock under impact (G-361, P-11314), H. Hartman, Pennsylvania State University: $77,500 (3 years) 1b, 1c, 3d(1)

182. Stress field in underground formations (G-19791, P-9334), Serata and Shosei, Michigan State University: $45,000 (2 years) 1a, 1b

183. Measurement of <u>in situ</u> rock stresses by hydraulic fracturing (P-18742), Fairhurst, University of Minnesota: $56,415 (4 years) 1a, 1b

184. An investigation of the strength of rock (P-16216, GP-2696), A. E. Schwartz, Clemson College: $9,030 1c, 2a(1)

185. Principles of stress field in underground formations, Serata and Shosei, Michigan State University: $73,559 (2 years) 1a, 1b

186. Correlation of seismo-acoustical properties of rock with elastic and anelastic phenomena (P-18960), Stefanko and Singh, Pennsylvania State University: $61,968 (2 years) 1b, 1c, 2a(2), 2b(2)

Appendix J

RESEARCH NEEDS IN ROCK MECHANICS—HIGHWAYS

Prepared by the Highway Research Board's Committee on Soil and Rock Properties (SGF-C2), Dr. G. A. Leonards, Chairman. This list will appear with a more extensive list of research needs in a future issue of Highway Research Circular.

C2-1 Problem: STABILITY ANALYSIS OF ROCK CUTS

Problem Area: The methods available for selecting safe slopes for rock cuts are unreliable. They are either general methods that do not account for geologic defects adequately or they are specific procedures whose limitations are not defined.

Objective: Develop analytical methods to evaluate stability of rock cuts that can consider the geometry, intrinsic stresses, rock type, geological defects, and the effects of groundwater and gain or loss of moisture content on exposure.

Urgency: High priority. Badly needed to increases safety and reduce costs of rock cuts.

C2-2 Problem: MECHANICS INVOLVING ROCK STRESSES IN DEEP CUTS

Problem Area: Some deep rock cuts have evidenced disturbance in the rock remaining due to the relief of restrain brought on by the cut. This disturbance has caused the popping out of rocks along the lower exposed faces, sometimes causing a traffic hazard.

Objective: To develop the mechanics involved to the extent that prediction of this action can be made in order to design restraint or protection devices.

Urgency: Will grow more urgent as these deep cuts become more common with modern design and construction.

C2-3 Problem: STRESS TRANSMITTAL FROM END BEARING PILES OR CAISSONS

Problem Area: The assumptions on stress transmittal from end bearing piles or spread foundations need both qualitative and quantitative substantiation. Many times designs are more costly than need be because of unrealistic assumptions of load transfer.

Objectives: (a) To develop design criteria for load transfer from end bearing piles and caissons to the underlying rock.

(b) To establish test methods to substantiate or disprove the proposed criteria.

Urgency: Many more dry land bridges will be constructed under the modern highway program with limited accesses. The economy which could evolve will be of growing importance.

C2-4 Problem: TO DEVELOP CRITERIA FOR PRESPLITTING

Problem Area: Presplitting of rock faces in cut excavations is becoming more and more common because of the reduction in overbreakage and therefore construction costs. Post construction maintenance costs are decreased since clearing of rock fall is reduced. The additional hazard of rock in the roadway is reduced also.

Objective: Evaluate the effectiveness of criteria for presplitting in relation to rock type, geological conditions, and height of cut.

Urgency: This information is needed to make competent designs of rock cuts with economical specifications and controls.

C2-5 Problem: MECHANICS OF ROCK SWELL AND CREEP

Problem Area: Movements of massive rock cuts against bridge abutments, etc., has caused structural distress involving expensive maintenance and repair. Rock swell into the bottom of some cuts has caused dangerous pavement damage, again leading to expensive maintenance or repair.

Objectives: (a) To develop measuring device and system to follow accurately the incremental rock swell or creep.

(b) To develop the mechanics of rock swell and creep so that accurate predictions of movement may be made dependent upon rock type and stratigraphy.

(c) To develop criteria for use in design.

Urgency: The problem, while not a major one at this time, will increase in importance as Interstate and Primary road systems are constructed in mountainous country.

C2-6 Problem: MEASUREMENT OF ROCK PROPERTIES OF CONCERN IN HIGHWAY CONSTRUCTION

Problem Area: There are no standardized tests for most physical properties of rock, and many of the existing tests are either time-consuming, expensive, or difficult to interpret.

Objective: To develop standard tests that are rapid and economical and still permit a high-confidence level in prediction of abrasion resistance, strength, porosity, absorption, density, and other rock properties that would be of use to highway engineers. To develop petrographic microscope analyses that would minimize or eliminate extensive laboratory testing of the aforenoted properties.

C2-7 Problem: USE OF GEOPHYSICAL AND OTHER NON-DESTRUCTIVE MEASUREMENTS

Problem Area: Geophysical techniques have been used in highway investigations to locate bedrock and, occasionally, to determine the depth and thickness of soil types that have distinctly definable signatures for the type of instrumentation used. These investigations generally are accompanied by extensive drilling and core sampling with subsequent laboratory tests. Considerable judgment still is required in deciding the most efficient method of excavating and processing the rock.

Objective: Information that can be used to ascertain the most efficient method for rock excavation; for example, whether (1) high- or low-energy chemical explosives will be most efficient, (2) draglines can be used, or (3) rippers will perform efficiently.

C2-8 Problem: RAPID EXCAVATION OF ROCK IN OPEN CUTS AND TUNNELS

Problem Area: Present rock and soil excavation methods are not always compatible with the rapid progress desired in building Interstate highways. Also, most of the rock excavation methods require high-energy explosives that could damage structures adjacent to those stretches of highways especially in the vicinity of urban areas. Furthermore, the feasibility of proposals to place Interstate highways underground through dense urban areas and to construct underground parking complexes is dependent on new and highly efficient methods of rapid rock excavation; such methods also will have to minimize possibility of structural damage to overlying buildings.

Objective: To develop methods not dependent upon conventional high explosives for excavating of all types of rock, such as fullface tunnel boring machines, thermal jets, lasers, high-frequency electrical arcs, and chemical explosives more controllable than those available today.

Urgency: There is a high priority on the development of such methods. It would open up new vistas for construction of high-speed transportation systems.

C2-9 Problem: METHODS OF DRILLING HOLES FOR EXPLOSIVES

Problem Area: The currently used methods are found on rotary, percussive, and rotary-percussive principles that have hardly changed for several decades. Conventional methods of excavating rock (drilling, blasting, and mucking) include a time-cycle that is controlled by the time required to get a drilling machine (or machines) into place, drill the hole, clean it, load it, and then remove the machine prior to blasting.

Objective: Development of very rapid hole-drilling methods that would use light-weight, easily and rapidly movable equipment, and maintain a clean hole during the entire drilling cycle.

Urgency: Large economic benefits would accrue in many aspects of highway construction, including rock cuts, production of aggregates, etc.

C2-10 Problem: PREDICTION AND CONTROL OF PORE PRESSURE IN ROCK MASSES

Problem Areas: Little is known about the relation between rock type and structure and the development of internal pore pressures in the rock; the same problem occurs where there is movement of water through rock masses. Water pressures can result in destruction of retaining walls (by uplift or by high back pressures caused by drainage from adjacent rock banks), unexpected movement of embankments founded on rock, undesirable deflection of concrete structures such as bridge abutments and the like.

Objective: Development of analytical and experimental techniques to predict pore pressure and groundwater movement in all types of rock and geological situations.

Urgency: High priority. Badly needed to increase safety and reduce costs of rock cuts.