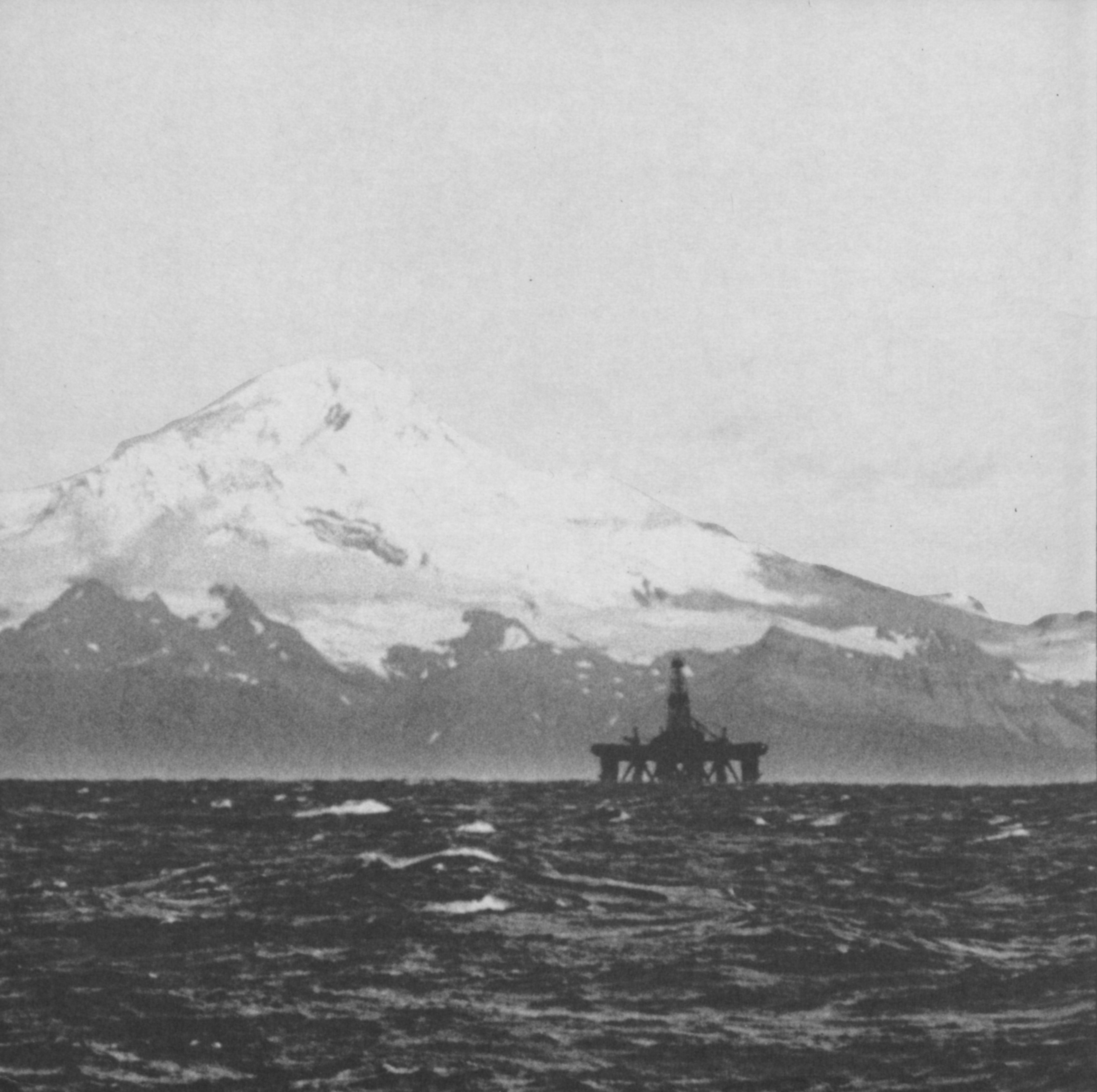
# ENGINEERING

## CORNELL QUARTERLY

VOLUME 13
NUMBER 4
APRIL 1979

BUILDING ON
THE SURFACES
OF EARTH



# IN THIS ISSUE



***Engineering: Cornell Quarterly,* Vol. 13, No. 4, April 1979. Published four times a year, in April, July, October, and December, by the College of Engineering, Carpenter Hall, Campus Road, Ithaca, New York 14853. Second-class postage paid at Ithaca, New York. Subscription rate: $5.00 per year.**

*Opposite: A drilling rig in Cook Inlet, Alaska. An offshore structure in this area is exposed to severe foundation loading because of ice impact, large tidal variations, and earthquakes.*

# PERSPECTIVES IN GEOTECHNICAL ENGINEERING

*by Robert L. Schiffman*

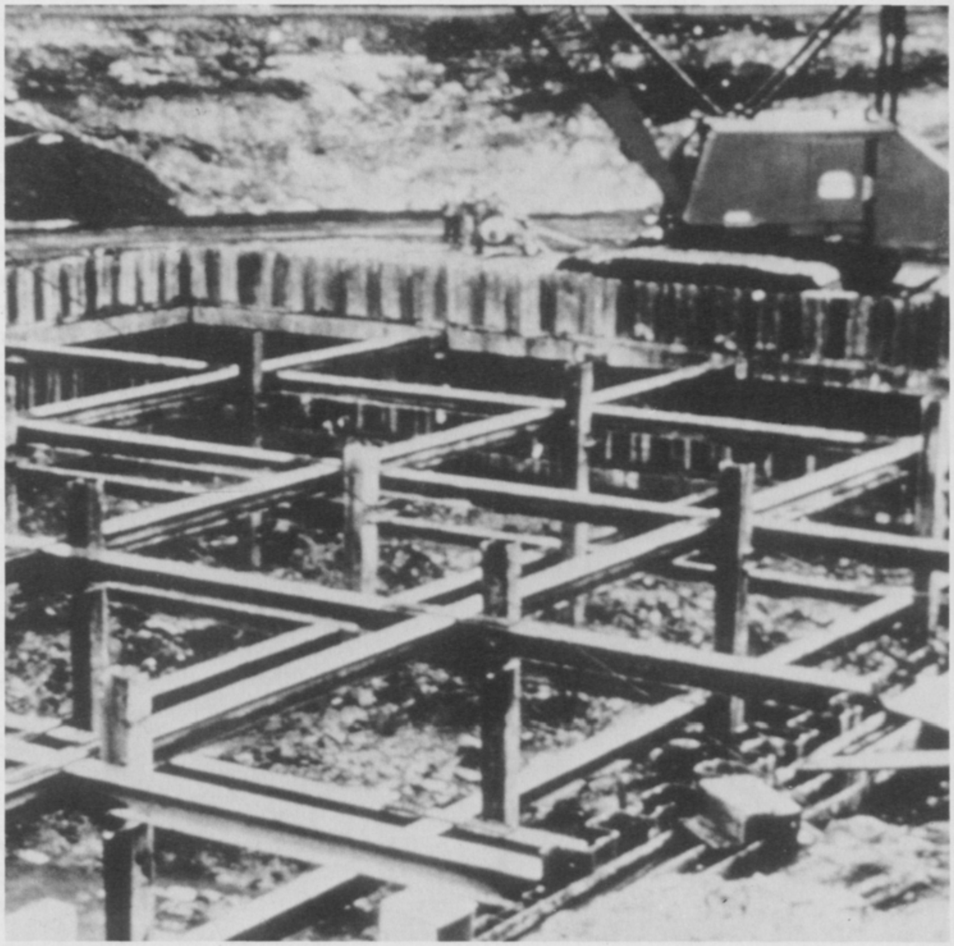
In pre-Biblical times the Egyptians constructed dikes to control the flooding of the Nile. Modern societies are meeting supply and control problems by building structures such as huge dams, pipelines hundreds of miles long, giant oil-drilling platforms on the seafloor, and mining shafts extending deep into the ground. All these projects involve work with rock and soil, the earliest engineering materials and still the basis for building on this Earth.

Modern geotechnical engineering started as soil mechanics with the work of Karl Terzaghi in the 1920's (see the photograph on page 38). Terzaghi's theory of consolidation, which was soundly based on the principles of mechanics, placed the subject on a rational and quantitative basis. Moreover, since the theory could predict the compression of a soil-water system subjected to foundation loads, it was useful in real situations. The major engineering contributions of Terzaghi (who was trained as a geologist) combined mechanics, geology, and superb engineering intuition in the solution of field problems: he founded not only soil mechanics, but also rock mechanics and modern engineering geology, and his work epitomizes what we today call geotechnical engineering.

## CURRENT WORK IN TRADITIONAL AREAS

Traditionally the geotechnical engineer has been concerned with the design and construction of foundations for buildings. The essential problem is to provide a safe and economical system that will transfer building loads to the ground. Safety is viewed in broader terms than the rare catastrophic failure of a building; it includes the control of settlement to avoid the cracking of internal partitions and the disruption of lifeline services such as gas and water supplies. But engineering skill is most critically tested when the design is controlled by economic factors and by the necessity of making sure that the foundation construction will not adversely affect existing structures in the vicinity. For example, a building may be supported either on piles, which minimize settlement, or by a shallow foundation, which is usually less expensive; with skill, the engineer may be able to design a shallow foundation so that settlements are kept within tolerable limits. Other problems may arise when buildings require deep excavations and dewatering of the site to permit construction. The geotechnical engineer may need to provide bracing to maintain the integrity of the excavation and to prevent damage to surrounding structures. It is also the engineer's responsibility to design pumps and recharge wells if these are necessary to keep surrounding structures from settling more than a tolerable amount as a result of the dewatering process.

The current severe problems faced by the United States in the area of transportation also present new challenges to geotechnical engineers. A major national effort is under way to divert traffic from highways by encouraging the use of track-supported vehicles, and stable, easily maintained roadbeds will need to be designed. Dynamic effects associated with high-speed trains must be examined, and the designs must take into account the close tolerances required for control of the



*The design of building foundations is a traditional area of geotechnical engineering. At left is a braced excavation in an urban area. The photograph below of a tilted grain elevator is an example of what can happen when a foundation provides inadequate bearing capacity.*

interactions between track and ground support system.

The control of water is another important area for geotechnical engineers today, as it was for their predecessors in ancient times. Dikes built of geologic materials are needed to control river flow and to protect against ocean storms, and earth and rockfill dams are used to impound water for irrigation, recreational uses, and electric power production. The construction of large dams has made dam safety an important concern. Many of the advances in slope stability research had their origins in the failure of the Fort Peck Dam some forty years ago. And the effect upon the profession of the more recent tragic failure of Teton Dam in Idaho has been broad. The investigations that followed opened up new areas of design and research, including studies of hydraulic fracturing of earth structures, the design of new construction procedures to enhance the safety of earth dams, and the development of new field instrumentation to enable engineers to discover and remedy potentially critical situations before catastrophic failure can occur.

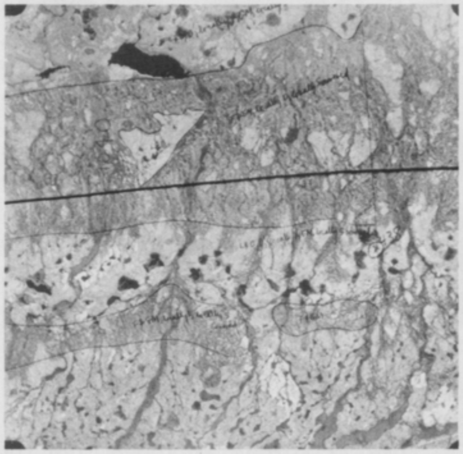
## NEW ENERGY-RELATED GEOTECHNICAL PROBLEMS

The energy crisis has created a myriad of new geotechnical engineering problems.

An example is the design and construction of large pipelines to move oil and gas from the North Slope of Alaska to the contiguous United States. These pipelines had to cross ecologically sensitive zones in an efficient, safe, and

1

2



*New kinds of construction challenge the skills of geotechnical engineers.*

*1. The design of pipelines from the Alaskan oil fields required special attention to environmental conditions. Specialists from Cornell participated in siting and foundation studies.*

*2. This airphoto (courtesy of Professor Ta Liang) shows a proposed pipeline route in a region of arctic Canada. The route was selected to avoid swampy peatland (light areas) and bodies of water (darkest areas). The darker land areas are mineral soil.*

*3. Winter drilling for soil and rock samples, part of a siting study, was conducted in temperatures as low as –60°F. In the background is a mobile laboratory for testing the specimens. The photograph is by Professor Liang, who served as a consultant for the project.*

*4. In an earth dam, zones of different materials serve different functions in providing a safe and impermeable structure.*

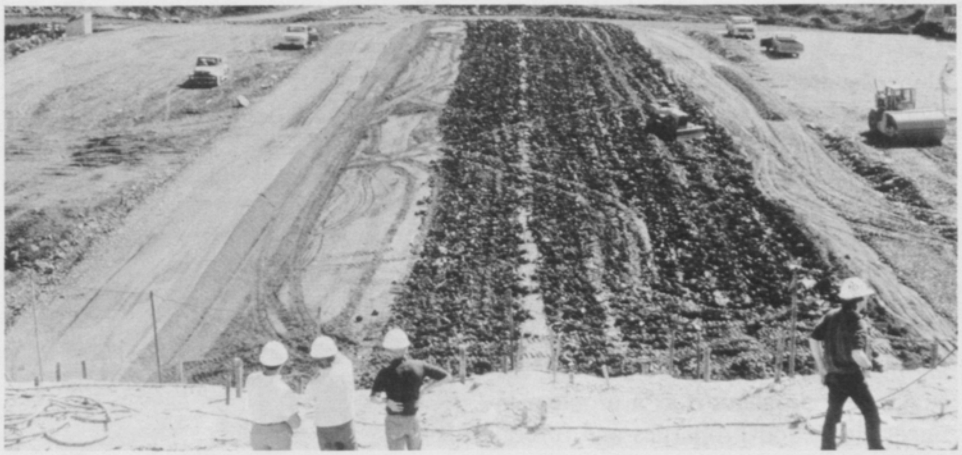
*5. Supervision of the spillway excavation for a dam is the responsibility of geotechnical engineers.*

*6. This production platform in the Gulf of Mexico is an example of the large permanent offshore structures that must be provided with stable foundations.*

3

*". . . rock and soil, the earliest engineering materials, (are) still the basis for building on this Earth."*

4



5

6

environmentally sound manner; for example, they had to be designed so that they would convey hot products through permafrost regions without softening the frozen ground and thereby causing failure of the foundation. The designs required a new form of analysis based on studies of the effect of extreme temperature changes on soil properties.

Geotechnical engineers are directly involved in the attempt to develop economically feasible processes to extract petroleum products from tar sands and oil-bearing shale. The development of geothermal energy sources, another area of great activity, involves similar engineering problems. In underground operations for the extraction of coal, oil shale, or geothermal products, engineers must be concerned not only with the mining problems, but also with possible problems of land subsidence.

One of the most recent, and most fascinating, challenges to the geotechnical engineering profession is in the area of marine geotechnology. Large, very complex structures are being founded on the sea bed for the purpose, among others, of developing oil and gas fields. Since these structures are subjected to ocean storms of great magnitude and long duration, the foundation requirements are formidable. Furthermore, the soil conditions are some of the worst in the world; the ocean sediments are usually soft and unstable. Even sampling the soil is difficult. The geotechnical engineer is faced with the problem of determining soil properties and designing a foundation system against a background of uncertainty and unfavorable loading conditions.

## NEW CRITERIA AND TOOLS IN GEOTECHNICAL ENGINEERING

All of these various geotechnical problems must be considered in terms of natural hazards such as floods, earthquakes, and tornadoes. Geotechnical engineers must continually be conscious of the need for analytical methods that can be used to accurately predict the effects of natural hazards, and for design and construction procedures that will provide protection against natural disasters or mitigate their effects.

One of the new approaches is the use of reliability, risk, or probabilistic analysis. From the beginnings of engineering practice, analyses and designs had been based upon the assumption of determinism. To compensate for uncertainties, large factors of safety were incorporated into designs. This luxury is no longer possible, however; the economics of construction requires that margins of safety be limited. Now, instead of treating a problem as having an inherently deterministic solution, the engineer approaches it as a problem in uncertainty. Soil properties and forces, for instance, are characterized by a probability distribution; instead of a "safe" slope with a specific factor of safety, the design provides for a slope that has associated with it a particular and acceptable probability of failure.

In all the many aspects of their discipline, modern geotechnical engineers are meeting new challenges with new ideas and approaches. Their professional world is lively, exciting, and significant, for they are working to help solve some of the pressing problems of society.

---

*Robert L. Schiffman, a Cornell civil engineering graduate of the class of 1944, is professor of civil engineering at the University of Colorado at Boulder. He is recognized as a pioneer in the application of computers to the solution of civil engineering problems (see the photograph on page 1 of Schiffman as a graduate student working with an early computer). He is well known also for his work in consolidation theory.*

*His honors include the 1960 Hogentogler Award of the American Society for Testing and Materials. He has been elected as an Overseas Fellow at Churchill College, Cambridge University, and has served as a Fulbright Fellow at the University of Zagreb, Yugoslavia, and as a Senior Scientist at the Norwegian Geotechnical Institute in Oslo, Norway. He has organized and chaired various national and international meetings on geotechnics, soil mechanics, and computer techniques, and he recently led the delegation to the joint United States–Yugoslavia Symposium on Computing, sponsored by the Department of State. He is also active as a consultant.*

*After graduating from Cornell, Schiffman studied for the M.S. degree at Columbia University and the Ph.D., granted in 1960, at Rensselaer Polytechnic Institute. He has taught at Columbia, Rensselaer, Lehigh University, the Massachusetts Institute of Technology, the University of Illinois at Chicago Circle, and Northwestern University, as well as at Colorado. He joined that faculty in 1969.*

*He is a member of the American Society of Civil Engineers and an ASCE representative on the Accreditation Visiting Committee of the Engineers Council for Professional Development. He is a member also of the Canadian Geotechnical Society, the International Society for Soil Mechanics and Foundation Engineering, and a supporting member of the Transportation Research Board.*

# FOUNDATION ENGINEERING

## New Skills in an Ancient Art

### by Fred H. Kulhawy

*Every one then who hears these words of mine and does them will be like a wise man who built his house upon the rock; and the rain fell, and the floods came, and the winds blew and beat upon that house, but it did not fall, because it had been founded on the rock. And every one who hears these words of mine and does not do them will be like a foolish man who built his house upon the sand; and the rain fell, and the floods came, and the winds blew and beat against that house, and it fell; and great was the fall of it.*
(Matthew 7:24–27)

Structural integrity and economics: these are the two essential features of foundation engineering today as they were in ancient times. Throughout the history of engineering, the interaction between structures and the substances on which they are supported has been an important concern. References to foundation stability appeared as long ago as 2100 B.C. in the Code of Laws of Hammurabi, and familiar passages in the New Testament point out the fundamental criteria of strength and reasonable cost. During the past fifty years, however, as structures have become larger and taller and it has become necessary to build on less desirable sites, there has been a greatly increased need to understand the complex problems of soil-structure interaction.

At Cornell, we are working on problems of uplift loading of foundations in soil, settlement of rock foundations, and capacity of seafloor anchorages. All these studies have significance for present and future construction projects and are an integral part of the vigorous program in geotechnical engineering here.

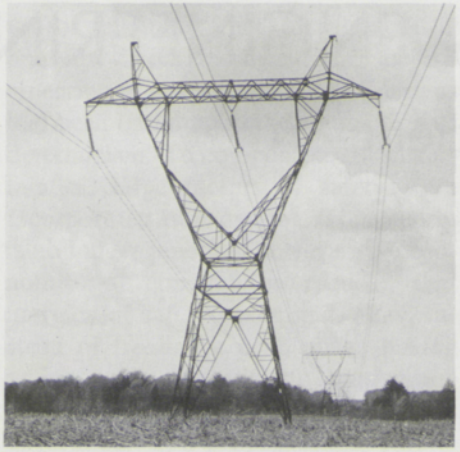
*For which of you, desiring to build a tower, does not first sit down and count the cost, whether he has enough to complete it? Otherwise, when he has laid a foundation, and is not able to finish, all who see it begin to mock him, saying, "This man began to build, and was not able to finish."*
(Luke 14:28–30)

#### STUDY OF UPLIFT LOADING OF FOUNDATIONS IN SOIL

The large lattice towers that support power transmission lines are examples of the kind of structure in which large uplift loads are exerted on the foundation system. In a strong wind, one or two of the legs of a lattice tower will be in tension and the foundation will be subjected to a large uplift force.

The project at Cornell comprises comprehensive studies that we believe will yield a rational design methodology for uplift loading conditions. Because an important potential application of this research is in transmission tower construction, we have been particularly concerned with the drilled shaft foundations (see Figure 1) commonly used for these towers. And since utility companies have a special interest in the outcome of such research, it is appropriate that support for the project is provided by the Niagara Mohawk Power Corporation of Syracuse, New York.

The research program began with a laboratory study of the behavior of soil-concrete interfaces and is developing in several phases. Large-scale model testing is being used to determine failure

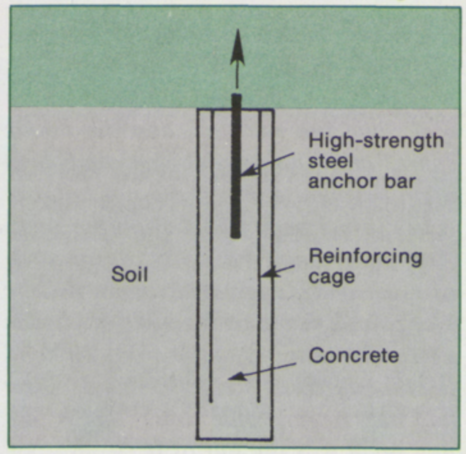


*Left: Drilled shaft foundations are suitable for structures such as this lattice transmission tower supporting 765-KV power lines. Problems of uplift loading on the foundation system are being studied at Cornell. (Photo courtesy of Niagara Mohawk Power Corporation.)*

*Left below: Models of foundations that will be subjected to uplift loading are tested in this circular chamber, about ten feet deep, which is filled with sample soil deposits. Professor Kulhawy is at left, with graduate student James P. Stewart.*

*Figure 1. A typical drilled shaft for a transmission tower foundation.*

***Figure 1***




modes and load-transfer mechanisms, and finite element modeling is used to express the behavioral characteristics quantitatively. After large-scale field tests have been analyzed, and the model testing has been completed, a design approach based on all the research findings will be formulated.

Already, significant results have been obtained. We have been able to determine that failure occurs essentially along a cylindrical shear surface around the shaft, a result that eliminates all the other previously hypothesized failure

*A construction site for Embarcadero Center in San Francisco shows the bracing for a foundation excavation.*

modes. We have also determined that the interface is, in nearly all cases, stronger than the host soil, which means that the capacity of the shaft is controlled by the strength of the soil. Since soil strength is controlled in turn by the in-situ stress state of the soil combined with the stress changes that occur during construction of the shaft, the influence of these stresses is being investigated in instrumented model tests. Our project work has also shown that the yield, ultimate, and residual capacities of drilled shafts, as well as the shaft deformations, can be predicted. It appears that the capacities and deformations can be computed with the use of simple expressions rather than more complicated finite element techniques.

The solution to the uplift loading problem, now in sight, will allow more rational and economical design in the future. Our study has also led to a number of side benefits, including the development of a sophisticated facility for testing large-scale model foundations and a new device for the accurate measurement of soil stresses.

## HOW FIRM IS A ROCK FOUNDATION?

A misconception that has persisted for thousands of years is that extending a foundation down to solid rock will prevent settlement. There are two fallacies in this notion. One is that there is such a thing as solid rock in an engineering context; the other is that settlement can be completely avoided. Actually, the rock masses that support foundations are composed of the rock materials and numerous kinds of discontinuity, including faults, joints, seams, and bedding planes. Furthermore, although settlement on rock is relatively small compared to settlement on soil, it may be significant. As the size of structures has increased, and as the design working stresses in the columns of the structures have been raised, the stresses on foundations have become greater. Also, new types of structures such as particle accelerators and radar tracking towers require exceptionally precise positioning. In many structural projects, the settlement of the supporting rock mass must be determined and taken into account in the foundation design.

Figure 2

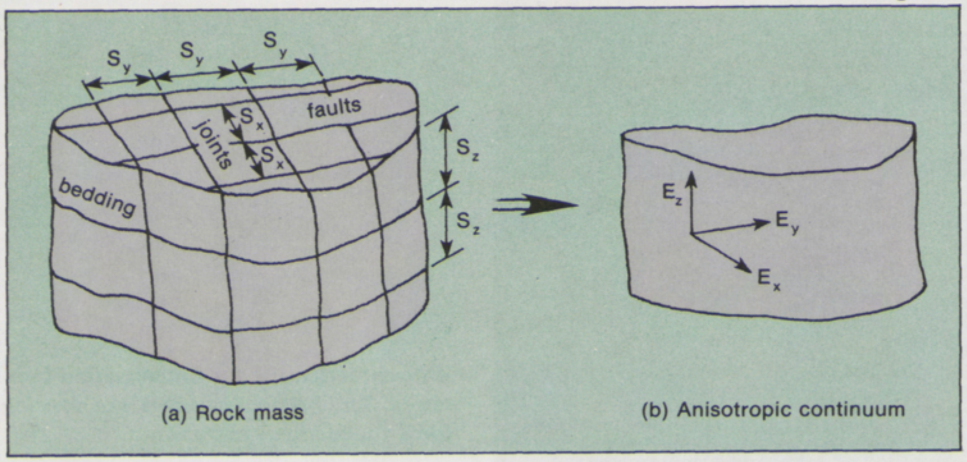



*Figure 2. Rock mass characterization as preparation for foundation design. (a) Analysis begins with the normalization of detected discontinuities such as faults, joints, and bedding planes to show mean spacings and orientations. (b) On the basis of the rock mass model and information on physical properties, an equivalent anisotropic continuum is formulated. With this continuum, the amount of settlement to be expected under a given foundation load is calculated.*

Figure 3

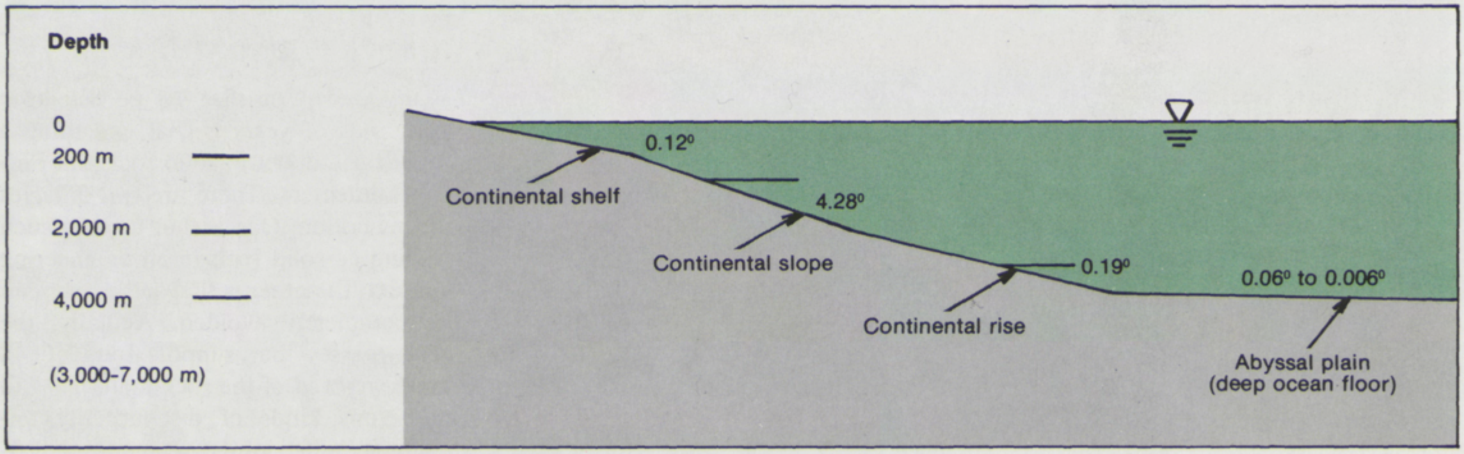



Figure 4

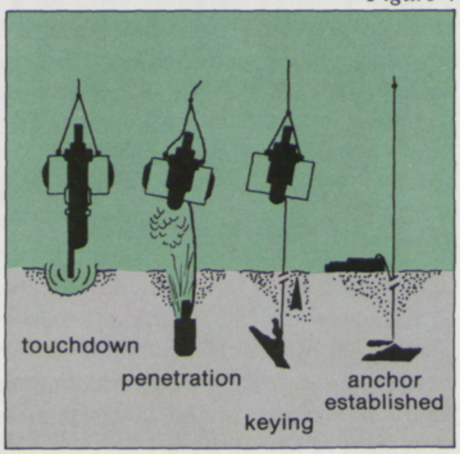



*Figure 3. A schematic of ocean floor, with average depth and slopes. Since various structures can require anchorage in any of these locations, an extremely wide range of conditions can be encountered. In addition to depth and slope, these include variations in seafloor material and wave action.*

*Figure 4. Embedment and keying of a propellant-actuated anchor. This type of system, developed by the Navy, has been studied to determine how well its capacity can be predicted under various marine loading conditions.*

The prediction of settlement is a formidable task because of the geologic complexity of rock masses. The only precise method is to conduct a full-scale test with prototype loading—a procedure that is rarely feasible. Reasonable estimates can be made, however, by using the Geomechanical Model developed at Cornell. This model is illustrated in Figure 2.

The first step in using the model is to characterize the rock mass. This is commonly done by conventional drilling and sampling techniques, sometimes

*"A misconception . . . has persisted . . . that there is such a thing as solid rock in an engineering context"*

supplemented by remote borehole logging and special sampling methods. An analysis begins with the normalization of the discontinuities to show mean spatial orientations and spacings (see Figure 2a). The second step is to establish the deformation properties of the rock material and the discontinuities. The sampled rock core can be tested in the laboratory to measure the moduli and Poisson's ratios (isotropic or anisotropic) of the material; the properties of the discontinuities are usually described in terms of normal and shear stiffness, which also may be measured in the laboratory. The third step is to establish an equivalent anisotropic continuum (as in Figure 2b) on the basis of the rock mass model and the information on physical properties. The final step is a computation of the settlement of the continuum under a foundation load.

Using this approach, we have determined solutions for circular, rectangular, and strip foundations on geologically complex media, and have obtained good agreement with field observations.

## THE CAPACITY OF SEAFLOOR ANCHORAGES

During the past two decades, facilities in the marine environment have become increasingly important and new areas of foundation engineering have opened up. Seafloor anchorage, for example, is now required not only for ships, including some of massive size, but also for pipe and utility lines, floating drilling platforms, and mining dredges. Other movable structures, perhaps including sea habitats, can be expected in the future.

Since any of these structures may be positioned anywhere in the oceans, each must be provided with a versatile foundation anchorage that can be deployed, efficiently, in depths ranging from the shallow continental shelf to the deep abyssal plain (see Figure 3). In addition, the anchorage system must be effective in a wide variety of foundation materials, from very soft, underconsolidated clays to hard, competent basalts.

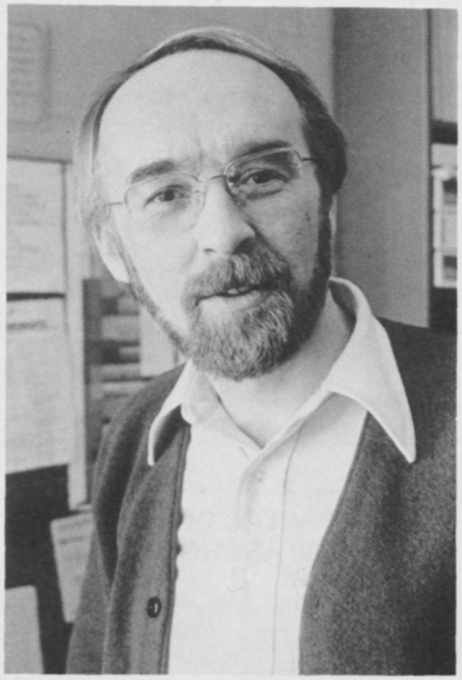
An anchorage system to meet these requirements has been developed by the United States Navy (see Figure 4) and we have recently conducted a state-of-the-art assessment of how well its capacity can be predicted under various conditions. In principle, the system consists of two parts, a gun assembly and an anchor-projectile. The complete system is lowered to the seafloor, the gun assembly "shoots" the anchor-projectile, or fluke, into the seafloor, and the fluke is keyed to establish the anchorage. Of course, details of the system vary depending on the size and material of the foundation.

In our study, the behavior of these direct-embedment anchors was examined under a variety of installation and loading conditions, and a number of critical factors related to capacity prediction were identified. In-situ stress conditions and the amount of disturbance during installation of the anchor were found to be important. The most signficant factor, though, was shown to be the strength of the supporting soil or rock—a property that varies greatly according to the particular marine loading conditions, especially cyclic wave action, and the stress history of the material. Designs that take into account the particular problems encountered in specific applications will provide the safe and economical anchorage needed in a wide variety of seafloor activities.

## NEW DEMANDS ON AN OLD DISCIPLINE

The three examples I have given of current research in foundation engineering demonstrate the significance and vitality of this field today and suggest the importance of its functions in the future. Foundation engineering is certainly not a new discipline—indeed, it is one of the earliest of all the engineering skills and is a traditional component of the broad area of geotechnical engineering. It is not the newness of the field that lends it so much importance today, but rather the requirements imposed by new or rapidly advancing technologies. As structures become larger and more specialized, and as more difficult ground conditions are encountered, the criteria for foundations can only become more exacting, both technically and economically.

Foundation engineers must acquire better fundamental understanding of the interactions between foundations and their supporting media, as well as technical expertise in specific applications. In both research and practice, foundation engineering promises to be an exciting field for decades to come.



*Fred H. Kulhawy, a specialist in rock mechanics, foundation engineering, embankment dams, and tunnels, is experienced in both teaching and professional practice. Before coming to Cornell as an associate professor in 1976, he was a member of the civil engineering faculty at Syracuse University for seven years. He has worked as a soils engineer with Storch Engineers of East Orange, New Jersey; as an associate of the consulting firm of Raamot Associates in Syracuse; and as a geotechnical engineering consultant for projects in Canada, the Caribbean, and the Middle East, as well as in the United States. He is registered as a professional engineer in New York, New Jersey, Pennsylvania, and California.*

*Kulhawy earned B.S.C.E. and M.S.C.E. degrees at the Newark College of Engineering in 1964 and 1966, respectively, and the Ph.D. in 1969 at the University of California at Berkeley.*

*He has published more than forty papers, including studies of soil and rock behavior, slopes, embankment dams, and foundations. His recent research has concentrated on finite element modeling and large-scale model testing of foundations. Most recently, he has been involved in detailed analysis and development of soil stress cells, in the design of long-span culverts, and in geomechanical modeling of rock foundations.*

*He is active on national professional society committees and is a past president of the Syracuse Section of the American Society of Civil Engineers (ASCE). In 1974 he received the Edmund Friedman Young Engineers Award for Professional Achievement from ASCE.*

# MARINE GEOTECHNOLOGY: ADVENTURE IN ENGINEERING

*by Dwight A. Sangrey*

Offshore is the new frontier for geotechnical engineering.

While the underwater habitat may be but a dream at this point, the exploitation of mineral resources lying beneath the ocean surface is a present reality: offshore oil is big business around the world and the mining of other mineral resources is being actively developed. Concurrently, traditional offshore operations, such as the transport of extracted products through pipelines and communication using bottom-supported cable systems, are being expanded. In all of these projects, geotechnical engineers play a major role.

The intensity and sophistication of present and planned offshore activities make marine geotechnology a field of challenge and opportunity. Scientifically and technically, it is a rapidly developing discipline—and Cornell has been at the forefront of the activity since the beginning.

## CHALLENGES IN BUILDING UNDERWATER FOUNDATIONS

All engineering works require adequate foundations. Whether these works are built on land or on the sea bottom, many of the same principles apply, and the advances in marine geotechnology are in many cases paralleled by similar advances in more conventional geotechnical engineering. The marine environment presents special problems, however. Building under water on soft or unstable surfaces of unknown composition creates a whole new set of working conditions, and it is remarkable that the technological capability has advanced so rapidly. It was only three decades ago that engineers ventured into the marine environment with permanent offshore oil platforms. From the first fragile structures in a few feet of water, it was a giant advance to the present record structure standing in more than a thousand feet of water on foundation piles that extend an additional 450 feet below the sea bottom. Cornell researchers had a share in this development: the design of this huge platform entailed technology based on studies by the geotechnical engineering group here.

In marine geotechnology, as in all branches of geotechnical engineering, the evaluation of material properties is a major consideration. Each geotechnical problem is unique because each site and the soils and rocks at that site are unique; it is necessary to evaluate the engineering properties and distribution of all types of soil and rock encountered at a particular location. This constitutes a fundamental difference between engineering with soil and engineering with materials such as steel and concrete whose properties are already known or can be controlled. In the marine environment, materials problems are especially troublesome.

The first difficulty encountered by the geotechnical engineer offshore is in identifying the type of material on the ocean floor and determining its distribution. In contrast to subaerial projects, in which the engineer can survey the site and conduct relatively inexpensive exploratory drilling programs, offshore projects are located in territory inaccessible to ordinary exploratory techniques. Until recent times, the only alternative to direct inspection and on-site testing was to collect small samples of sea bottom using devices thrown over the

side of a ship. Core samples could be obtained with conventional drilling equipment mounted on a ship or barge, but boring programs of this kind are both expensive and technically complicated. Within the past decade, however, advances in applied geophysics have provided new approaches to the problems of site appraisal. High-resolution seismic profiling is becoming a standard technique and, more recently, side-scan sonar, which produces an image of the seafloor topography and material characteristics, has become available. These two tools (see Figures 1 and 2) have become the eyes and ears of the geotechnical engineer offshore.

Evaluating the materials found on the seafloor is the next problem. Soil types include not only those commonly found on land, but some with very unusual characteristics. On the continental shelf areas—generally out to a water depth of about two hundred meters—the soils are usually similar to those on adjacent land masses. In deeper waters, beyond the shelf break, the soils may be very different in origin and have unusual engineering properties. The deep marine seafloor is typically composed of highly organic soils, chemical precipitates, and extremely fine-grained mineral constituents. New and special methods, some of which were developed at Cornell, are required to evaluate the engineering properties of these various types of materials.

*The construction of this oil-production platform in the Gulf of Alaska presented especially difficult geotechnical engineering problems because of the hostile environment. Designs for recently constructed platforms such as this used technology developed by the Cornell geotechnical engineering group.*

Figure 1

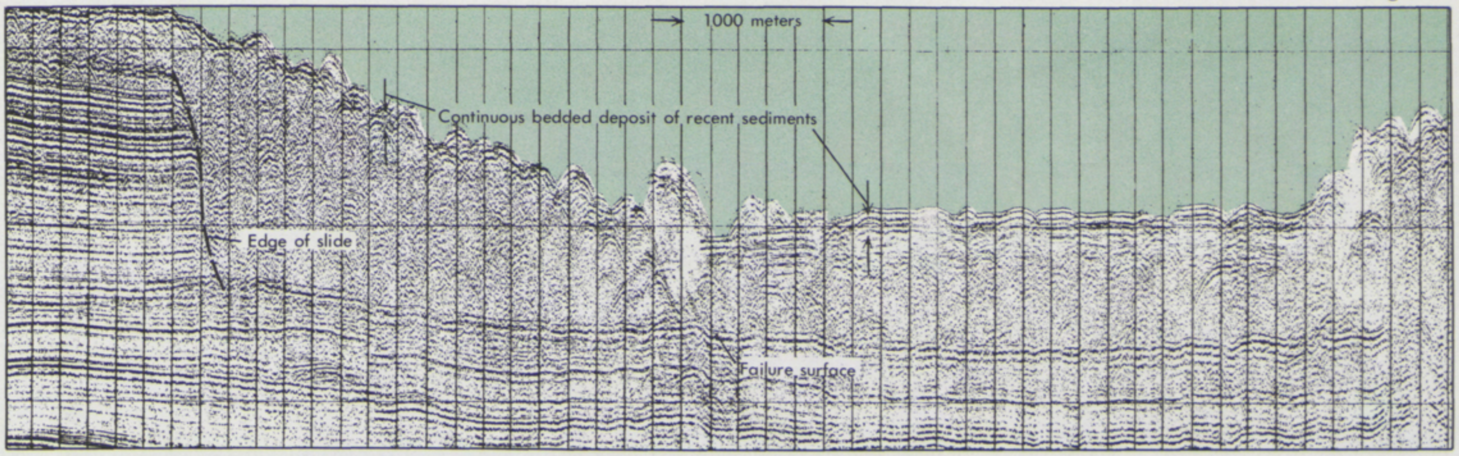
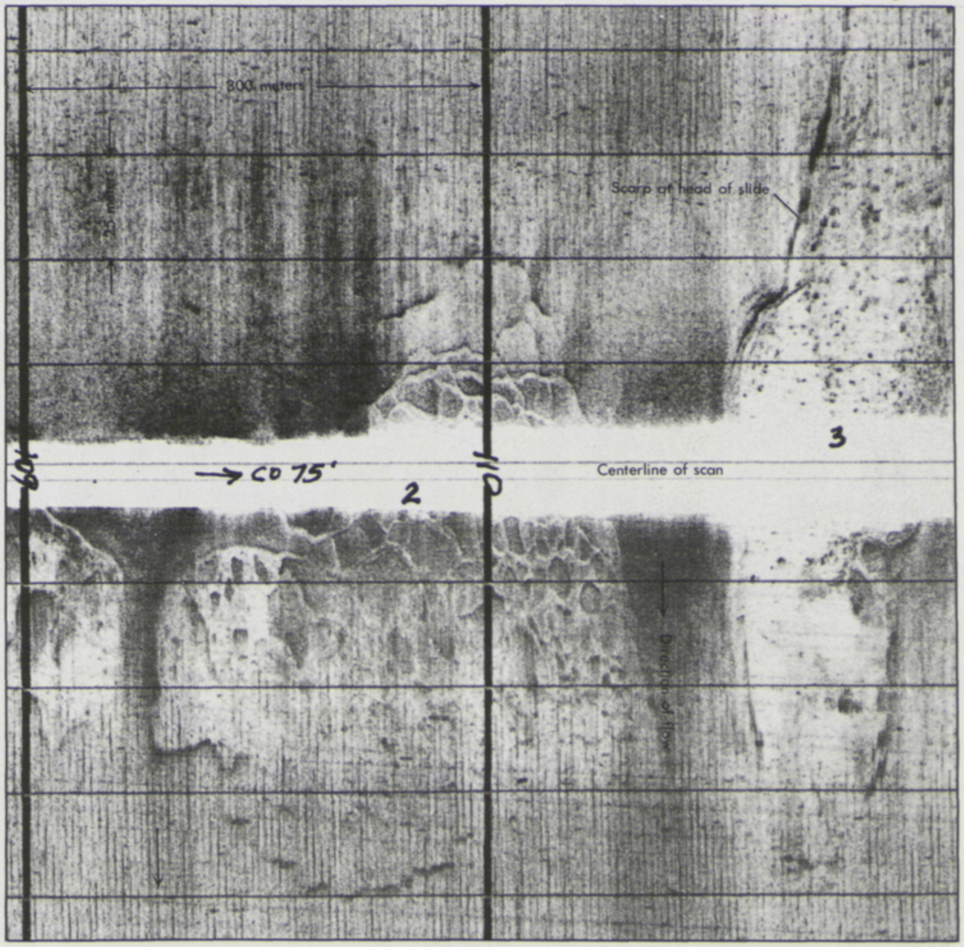



Figure 2




*High-resolution seismic profiling and side-scan sonar permit the geotechnical engineer to examine the seafloor where foundations must be placed for offshore structures.*

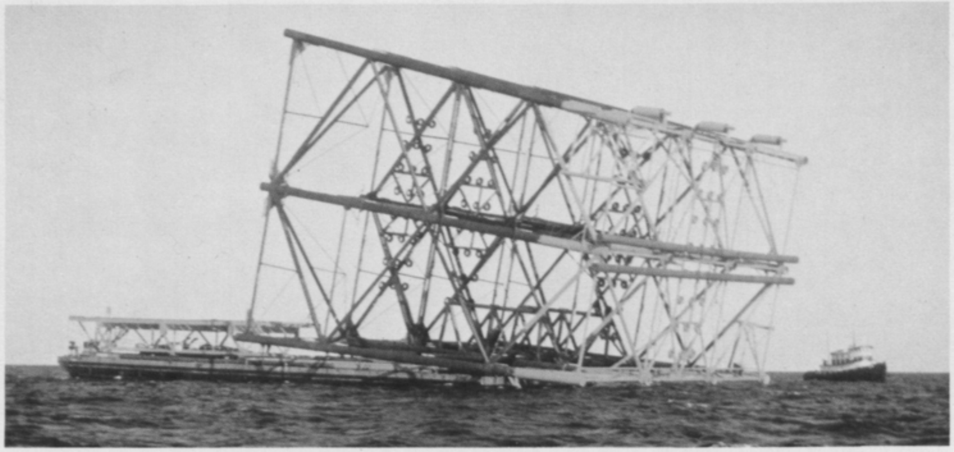
*Figure 1. A seismic view across a submarine landslide shows that the slide may be old and immobile. Although relatively stable, such slides can be reactivated by drilling. The vertical scale is magnified about eighteen times.*

*Figure 2. These side-scan sonar records show positions, sizes, and shapes of submarine mudflows.*

## SPECIAL ENGINEERING PROBLEMS OFFSHORE

The geotechnical engineer working offshore is faced with some particularly difficult engineering problems. For instance, the design of a marine structure must take into account not only ordinary loading, but also large and repetitive wave forces. Regardless of whether these forces act on a structure or on the sea bottom, they must be resisted by the structure and must be compensated for in the design.

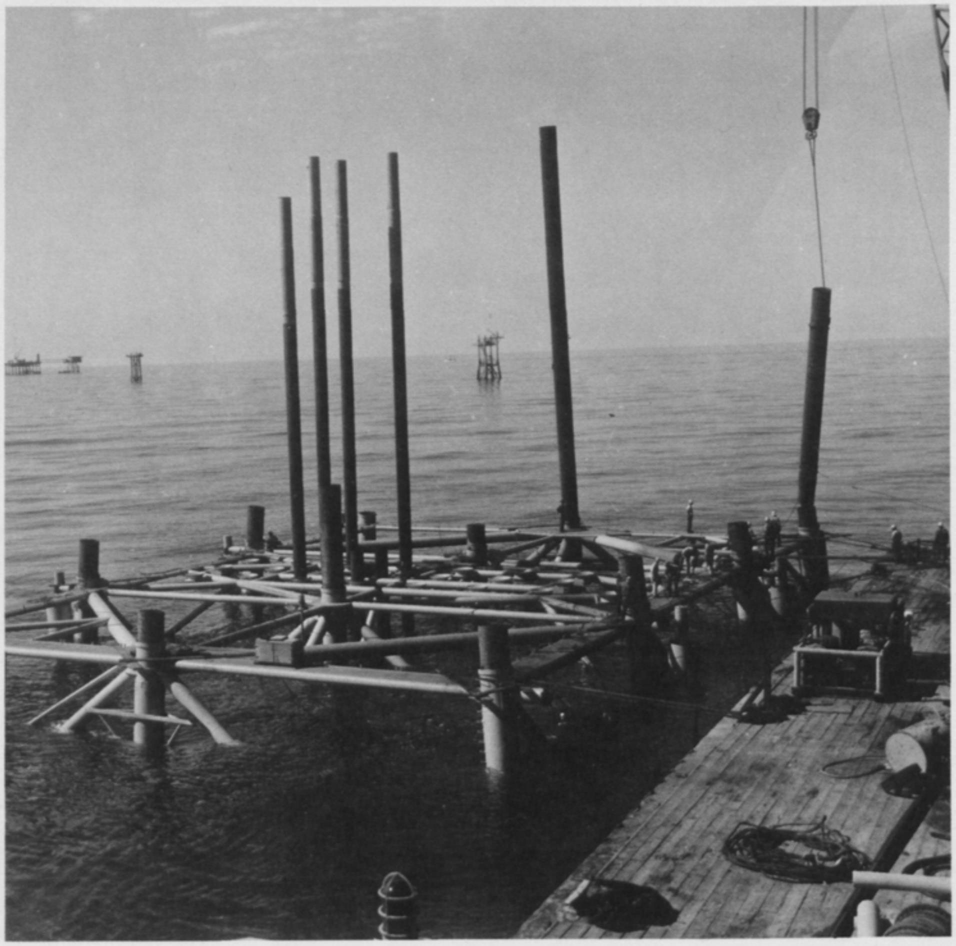
1



*A permanent offshore structure is prefabricated in large sections onshore and towed to an offshore location (1), where it is placed on the bottom. Foundation piles are driven through the legs (2) to support the jacket and deck.*

*Exploratory offshore drilling for oil is done using large movable rigs which are towed to location (3) where they are anchored or temporarily supported on the seafloor. Offshore soil borings are also done from temporary platforms or drillships (4).*

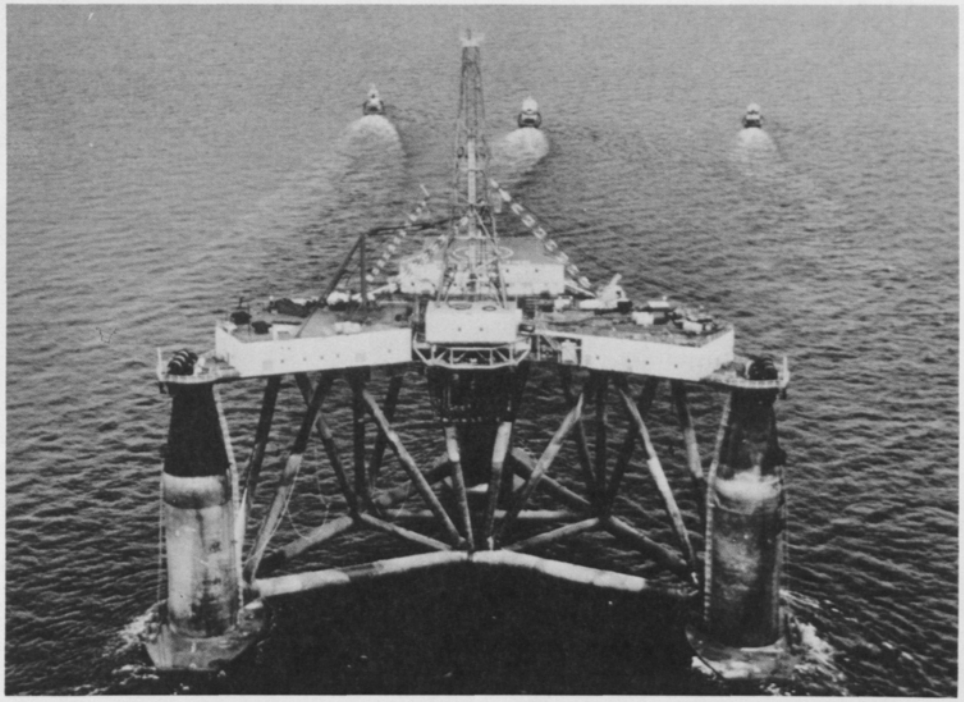
2



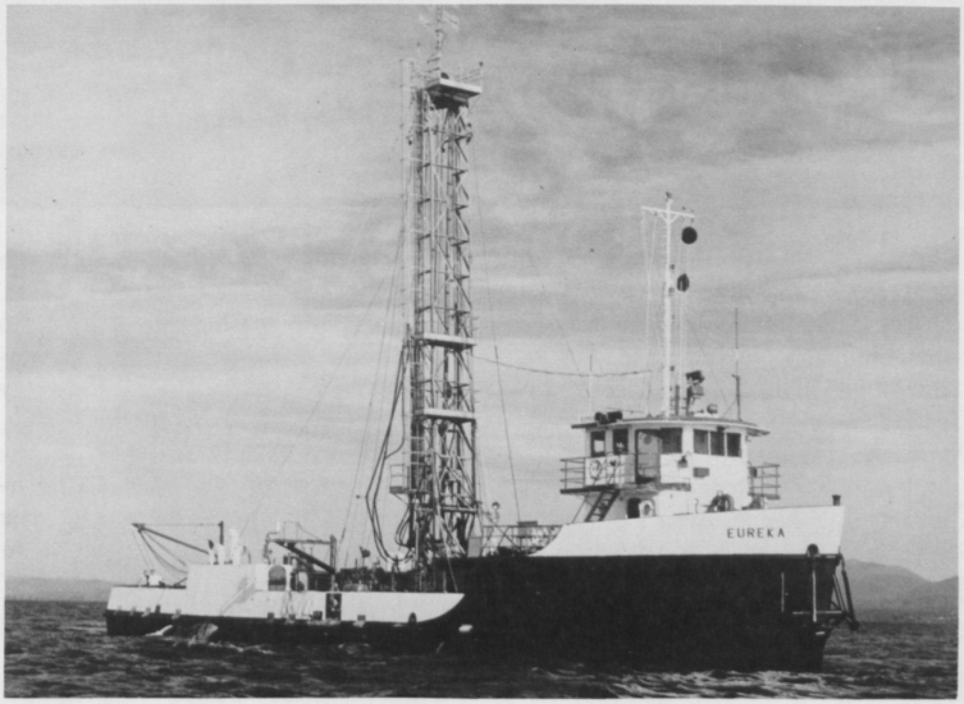
The seafloor does not always provide good support. At many locations the sea-bottom muds are extremely soft, and areas of active sedimentation like the Mississippi Delta present special problems because of underconsolidation. Methods for dealing with these difficult conditions are being developed in current geotechnical engineering research. A project at Cornell, for example, is directed toward problems of underconsolidation in areas of the Gulf of Alaska and the Atlantic.

Underwater landslides present another unique situation. Under the action of waves, earthquakes, or other unusual loads, large areas of the seafloor can give way in massive slides. These slides have caused the collapse of large offshore oil structures, they have been known to cut submarine telephone cables over a distance of a thousand kilometers, and they have, on occasion, produced immense ocean waves that caused onshore destruction of property and loss of life. For nearly a decade, the Cornell group has conducted research aimed at understanding submarine slides and minimizing the

3



4

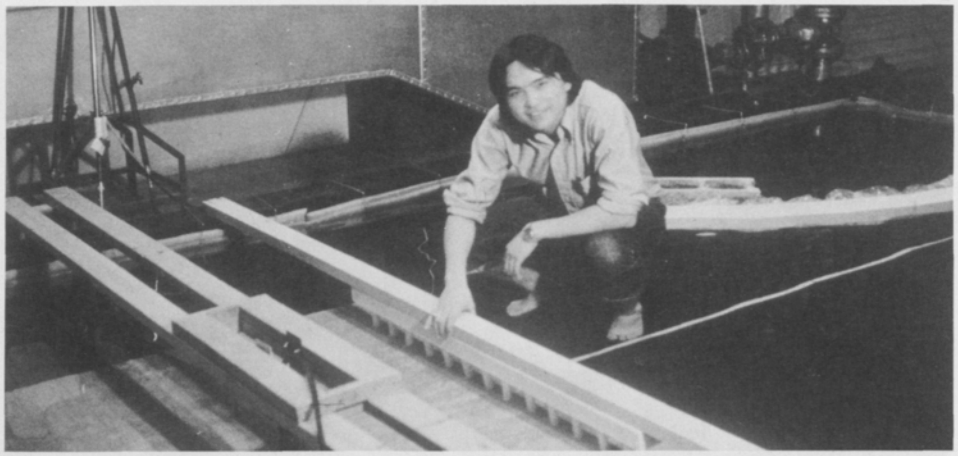



*"The action*
*of the sea*
*is dynamic."*

*Research at Cornell on marine geotechnical engineering problems has included work on pile foundations under dynamic loading (1), isolation barriers (2), and underwater landslides.*

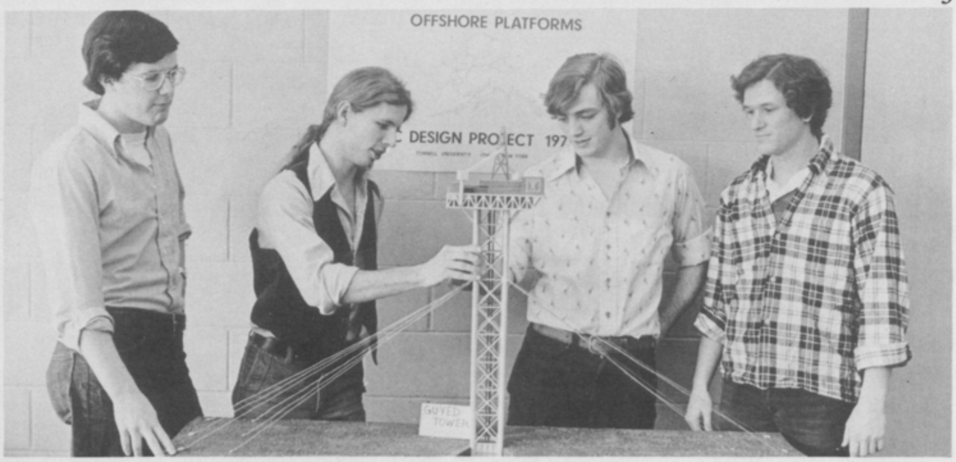
*Marine geotechnology has been part of the educational program also. For example, Master of Engineering (Civil) students (3) were part of a design group considering offshore structures and foundations. The model shown is an innovative guyed tower supported in part by anchored cables.*

*2*



*1*

*3*

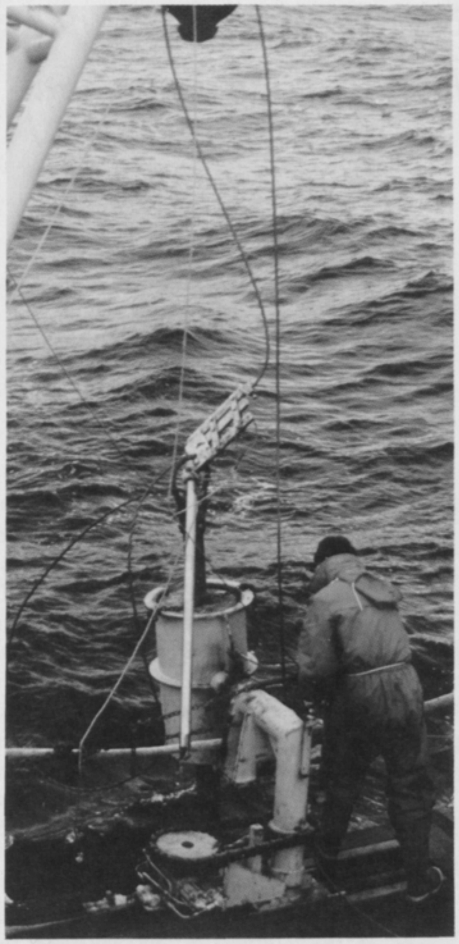



loss associated with them, and work in this area is continuing.

These special problems all exemplify the dominance of dynamic loading considerations in offshore engineering. The action of the sea is dynamic. Motion imparted to structures by the supporting seafloor is dynamic. Earthquake loading is dynamic. Even the live loading associated with construction and with the extraction of minerals is dynamic. Dynamic loading and its effects on material behavior is therefore an important area of research in marine geotechnology, and it is one in which Cornell has been active for some years. Research into the behavior of marine soils under dynamic loading was pioneered here, and many of the early fiindings are in general use today. Sophisticated analysis and design techniques, particularly finite element methods, have been employed in the last few years, and Cornell has been active in developing this capability also.

Offshore geotechnical engineering is precisely the kind of challenging activity that appeals to many young engi-

1



*Obtaining samples of core from marine bottom sediments not only is expensive but requires techniques not used on land. Cornell students and faculty members are currently involved in a research project in the Gulf of Alaska, in which piston coring is used to obtain specimens of soft clay for engineering tests. The coring equipment is prepared on the ship (1), lowered over the side (2), and allowed to penetrate into the bottom sediments. After recovery (3), the core barrel is opened to get at the payoff — a continuous section of marine soil (4). Professor Sangrey and some of his students are among the people pictured.*

2

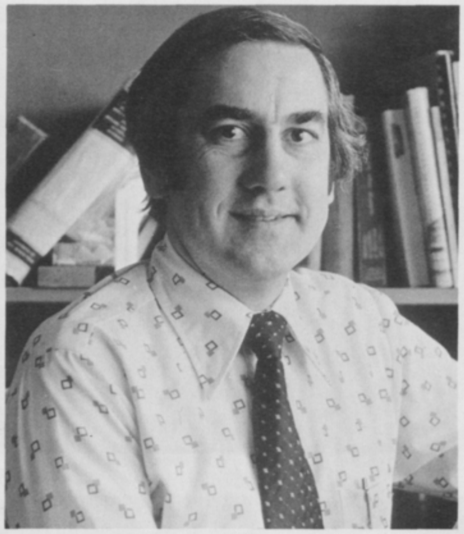
3

4

*"It was only three decades ago that engineers ventured into the marine environment"*

neers. Its practice combines highly sophisticated and innovative problem-solving with an unusually strong element of insight, intuition, and engineering skill. Many of the project sites are geographically remote and hostile; an example is the Gulf of Alaska and Bering Sea area, where two Cornell students are now doing their thesis research. In many respects, marine geotechnology offers the kind of "frontier" challenge that is absent from many kinds of engineering practice. The risks are very high and so are the rewards.

Opportunities for geotechnical engineers with a background in marine applications are among the strongest in all of engineering and promise to remain so. Likewise, the development of new skills, tools, and techniques will surely remain an active area of research. At Cornell we intend to remain at the front of this activity, meeting the needs of a vigorous, growing technology and providing its engineers with new challenges.



*Dwight A. Sangrey, a specialist in soil engineering, joined the faculty of Cornell's School of Civil and Environmental Engineering in 1970 after spending three years at Queen's University, Kingston, Ontario. Sangrey also was a graduate student at Cornell, earning the Ph.D. in civil engineering in 1968. He holds the B.S. degree from Lafayette College and the M.S. from the University of Massachusetts, both in civil engineering.*

*A registered professional engineer, he has had industrial experience with the Shell Oil Company as a field and project engineer specializing in offshore marine structures and foundations, and with H. L. Griswold Associates as a general consultant. He has been active in sponsored research in soil dynamics, marine geotechnical engineering, foundation engineering, slope stability, and physico-chemical attentuation of the soil. He has published extensively, most recently on cyclic loading of sands, silts, and clays, and on submarine landslides.*

*Sangrey has received three teaching awards from Cornell groups. In his second year at the University, he received the annual Excellence in Engineering Teaching Award given by the Cornell Society of Engineers and Tau Beta Pi; and twice in the past five years he has been chosen by Chi Epsilon for the Professor of the Year Award.*

*He is a member of the American Society for Testing and Materials and received a research award from that organization in 1969. Among other professional organizations to which he belongs are the American Society of Civil Engineers, the American Society for Engineering Education, the International Society for Soil Mechanics and Foundation Engineering, and the Transportation Research Board.*

# ENGINEERING GEOLOGY

## A Combination of Inseparable Fields

*by Richard E. Goodman*

Shortly after graduating from Cornell I was asked what I had studied as an undergraduate. "Geology? You're fifty years behind the times," was the response to my explanation. In these exciting times, when *geology, environment,* and *energy* are household words and trilobites are sold in Western drug stores, the attitude of the questioner seems incredible. Yet, in a sense, his judgment was right at the time: Job opportunity, which had once lured young men to the adventures of geological exploration in the American West, had diminished. The pendulum of interest and activity in geology had not yet swung back to a high position. As for me, I bided my time, acquiring a knowledge of civil engineering in preparation for what has unfolded as a fulfilling and stimulating profession.

Engineering geology, as this profession is called, is the modern embodiment of a long and close association of geology and civil engineering. It encompasses such diverse activities as evaluating hazards like eruptions, active faults, earthquakes, and landslides; finding optimal routes and sites for highways, dams, bridges, nuclear power plants, and other large structures; locating aggregates, rip-rap, and other construction materials; and "seeing" into the subsurface for the design of tunnels, rapid transit stations, underground powerhouses, and other underground facilities.

The planning and design of engineering works implies selection of the best site and the best scheme from a large number of possible alternatives. Geological factors figure prominently in the selection process, but as only one alternative is actually built, savings or penalties from accurate or faulty engineering geology are often conjectural. What is not conjectural is that good engineering in rock requires good engineering geology. Vital decisions for planning and design must be drawn from geological experience and judgment in close partnership with engineering calculations.

### GEOLOGY AS A FACTOR IN COLOMBIAN PROJECTS

The importance of engineering geology in planning and design is illustrated by some personal experiences in the developing South American country of Colombia. A growing population and a shortage of petroleum have forced Colombian officials to exploit the excellent potential for hydroelectric power provided by the country's abundant rainfall and mountainous terrain. Those feasible projects that are not already underway have probably been projected.

A great variety of geologic features are found throughout the country. The mountainous western half, where most of the people live, forms three ranges drained by two north-flowing rivers, the Magdalena and the Cauca. In the central and western mountain chains, intermediate intrusives and Paleozoic metamorphics predominate with an abundance of mica schist, and recent volcanics are found. The Magdalena and Cauca valleys are blanketed by Tertiary gravels and tuffs. In the East the predominant rocks are shales and sandstones of Cretaceous Age or Paleozoic basement rock, including limestone. In the region near the central plateau of Bogota, Tertiary and Quaternary lake and stream deposits with

Figure 1

*Figure 1. The Chuza dam site in Colombia. The view is into the reservoir area from a point just above the left abutment. The river flows directly toward the camera through the narrow notch, and not in the major valley on the upper left side of the photograph.*

poorly cemented sandstones, coal-bearing sediments, and clay appear in the sides of mountains and under the soil. Tilting and faulting of these relatively young deposits warn of active seismicity, and this is borne out by a dense network of active faults that spreads throughout the country.

This geologic variety is accompanied by all sorts of construction problems. The unpredictability of weathered rocks is well appreciated in Antoiquia, a region around the mountain city of Medellin, where almost all sites confront deeply decayed quartz diorite. The silty soils and steeply sculptured terrain engendered novel approaches in dam construction there. In some areas compaction shales, with their propensity for landslides, have forced relocations or repairs to powerhouses and penstocks. Tertiary sediments, squeezed by thrust faulting, have caused high earth pressures on shafts and tunnels. Landslides have cut off access to job sites and isolated towns. And cavernous limestone has complicated the siting and design of a large dam.

## DAM AND TUNNEL PROJECTS FOR WATER AND POWER

One of the first projects I participated in was the design of the Chuza Dam and Chingaza Tunnel, which were planned to convey water to Bogota. Since the city has an elevation of over nine thousand feet, and since water entering the city must also leave, a system for delivering water would also provide a means of generating power. Consequently, part of the cost of the exceedingly long tunnel system, extending thirty kilometers through the mountains, was to be offset by anticipated power benefits.

The dam site, shown in Figure 1, lies just downstream from a gravel-floored natural reservoir, where the river plunges through a canyon so narrow that the sky cannot be seen from within. Though it is close to the equator, the site has topographic and geologic features connected with the formation and destruction of a glacial lake, and glacial geomorphology determined the characteristics of foundations for a saddle dam. Since the canyon is carved

*Below: Professor Goodman (at right) served as an engineering geology consultant in Colombia in the early 1970's for a number of dam projects in the country's mountainous regions. The others in the photograph are a geologist and an engineer of Ingetec, Ltda., which engineered several of the projects.*

Figure 2. Excavation for the Chivor powerhouse in Colombia. Debris coming down the tributary creek on the left derives from slides in shales above and erosion during construction of the access road. The landslide on the bank opposite the powerhouse excavation is typical for this region and is part of the reason for placing the penstocks underground.

Figure 3. Chivor dam site, with the almost finished spillway excavation on the left and the half-completed embankment below. Note the crane in the spillway for scale, and the smooth discontinuity surface in the rock above. The light streak on the slope below the crane represents grout leaking from open rock joints and faults.

Figure 2

Figure 3

into shale mineralized with pyrite, we decided to build a rock-fill structure rather than one formed of concrete.

Exploration for the series of tunnels leading from the reservoir to Bogota was mainly by airphoto interpretation and field geology. Decisions on such features as the locations of portals, the siting of intake shafts, and the location of alternative routes were made on the basis of field work, limited drilling, and exploratory adits. Considering the length of the tunneling and the variety and complexity of geologic conditions along the way, the drill holes (which we completed with great difficulty) provided only a trivial sampling of rock types and conditions. This is frequently the case in the engineering of long, small-diameter tunnels beneath high mountains, but it was particularly true in this Chingaza project because of the relative inaccessibility, the very high altitude, and the hostile climate.

*" . . . good engineering in rock requires good engineering geology."*

On the other side of the range, in the foothills to the west of the great plains of Eastern Colombia, the Chivor dam and power project has been built in a steep canyon incised in Paleozoic metamorphics. The main features were sited largely on the basis of geology. From the reservoir, behind a rock-fill dam over seven hundred feet high, a headrace tunnel leads to a surface penstock where the crossing of the Santa Maria fault changes the geology abruptly for the worse—to Cretaceous shales. In the earlier Collegio power project, along the Bogota River, the designers had learned through a series of landslides that it is best to avoid extensive grading for penstocks in Colombian shales, and so the Chivor penstock was laid out, as far as feasible, along the natural terrain. When it approached the final steep descent to the powerhouse, the penstock was placed underground in a shaft and tunnel in order to reduce the chance of a landslide and remove the risks created by slope movements (see Figure 2).

The spillway of the Chivor dam, shown in Figure 3, is a steep open cut benched into the side hill, with an unexcavated spur of rock dividing the embankment from the spillway channel. During construction, a smooth fracture surface, dipping toward the spillway gate, was revealed in the rock wall; to avoid undermining this rock, it was decided to narrow the channel and increase the surcharge on the gates. The radial gates that resulted from this design change are among the highest in the world. Several slides of rock have subsequently occurred along the smooth discontinuity surface in the spillway slope—the most recent partly buried one of the gates—and analysis of these slides has provided the basis for a plan of excavation to protect the project from further landslides. Finding ways to spill a reservoir harmlessly, without erosion, cavitation, or rock slides, and with economy, continues to be one of the most difficult engineering problems encountered in the Andean hydroelectric power developments.

A third project involved a high rock-fill dam, a long power tunnel, and an underground powerhouse in the Guavio region. The layout is similar to Chivor, which is nearby, but Guavio proved to be very different because the dam site is in limestone. Caverns in the reservoir confirmed that reservoir leakage was a potential problem. But geologic mapping showed that the cavernous rock is confined to Cretaceous formations separated from the Paleozoic limestones and metamorphics at the dam site by an angular unconformity. Regional geologic mapping of the Cretaceous limestone determined that the only possible leakage paths were around the abutments, and these were explored carefully. A line of deep drill holes crossing the valley at the dam site showed water levels above reservoir elevation with gradients toward the valley, establishing the valley as a region of discharge rather than one of recharge of ground water.

Engineering geology in the central Cordillera range has also provided geologic information that has had a bearing on important engineering decisions. Along the Cuaca River, we located a series of seven run-of-the-river power dam sites, one of which is now in design. From the regional map-

ping, we chose sites to avoid major faults, to stay out of mica schist, and to provide work sites free from rock falls and landslides. Along the Miel River, a tributary of the Magdalena, we located the powerhouse underground in schist in preference to hydrothermally altered quartz diorite, and we compared alternative schemes on the basis of dam site quality, materials, and relative tunneling costs.

## ENGINEERING IMPORTANCE OF UNDERSTANDING ROCK

From these experiences I have learned that civil engineering and geology are as inseparable today as they were in years past. The outcome of predictions, sometimes satisfying, sometimes frustrating, makes this a challenging branch of geology.

Novel engineering developments ensure that engineering geology will remain important and demanding. These relate to underground storage and conversion of energy resources; the disposal of nuclear wastes in subsurface formations; the siting of nuclear power plants underground; drilling for petroleum from tunnels under the sea; the development of oil shale reserves; the creation of new materials like high-strength concrete in which rock is used more efficiently; and the suspension of bridges from valley sides with cables. Central to all these operations is the description, appreciation, and analysis of the morphology and properties of rock.

*Acknowledgments: The Chingaza, Chivor, and Guavio projects were engineered by Ingetec Ltda., Bogota; the Cauca River engineering is by Integral Ltda., Medellin; the Miel project is being studied by Consorcio Rio La Miel, Bogota.*

*Richard E. Goodman spent the 1978 fall term at Cornell during a sabbatic leave from the University of California at Berkeley, where he is professor of geological engineering. He holds Cornell degrees in geology (the B.A., granted in 1955) and engineering science–civil engineering (the M.S., 1958), and received the Ph.D. in geological engineering from Berkeley in 1964. He has been a member of the faculty there since completing the doctorate.*

*His experience includes employment with several geotechnical engineering firms and the Corps of Engineers. During his graduate-student years at Cornell, he worked as an airphoto geologist with a consulting firm headed by Cornell Professor Donald J. Belcher. He serves as a consultant in engineering geology and rock mechanics, and as principal investigator on a number of research projects.*

*Goodman's honors include a Guggenheim Fellowship in 1972, the 1976 Rock Mechanics Award of the American Institute of Mining and Metallurgical Engineers (AIME), and the 1977 Burwell Award of the Geological Society of America. He has published more than eighty professional papers and reports, as well as a book,* Methods of Geological Engineering in Discontinuous Rocks *(West, 1976). Another book,* Introduction to Rock Mechanics, *will be published by Wiley next year. He is a member of the American Society of Civil Engineers, the Society of Mining Engineers of AIME, the American Geophysical Union, the Association of Engineering Geologists, and the Geological Society of America.*

# FRACTURE MECHANICS

## A New Tool for the Geotechnical Engineer

*by Anthony R. Ingraffea*

To the geotechnical engineer, fracture is both a problem and a tool. In mining and excavation, for example, rock fracture must be controlled in order to ensure safety, but it must be induced for efficient operation. Especially in recent years, as the pressures of new technology and energy-resource depletion have placed new demands on the engineer's ability to work with rock and concrete, an understanding of fracture has become essential. The control of induced rock fracture is a key element in the efficient extraction of energy resources; proposed underground storage of hazardous wastes will require knowledge of rock fracture modes; a variety of new construction applications depend on the control or use of fracture.

In solving such problems, the geotechnical engineer is now beginning to use analytical methods developed in the engineering field called fracture mechanics, which is based on concepts of stress analysis and material science. Specifically, fracture mechanics is concerned with stress and material behavior near a crack front, and the onset, rate, and direction of crack propagation.


*Professor Ingraffea and graduate student Susan Ronan use new electronic servo-controlled equipment for testing the fracture toughness of rock or concrete.*

### THE NEW EMPHASIS: A RETURN TO EARLY IDEAS

The field of fracture mechanics originated in the 1920's with A. A. Griffith's work on fracture of brittle materials such as glass and rock. Its greatest development, though, has occurred during the past twenty years, as the aerospace, shipbuilding, pressure vessel, and pipeline industries have directed research efforts toward the study of fracture of metallic structures, in which truly brittle behavior is rare. The objective of most of this basic research has been to modify Griffith's ideas or to propose new concepts to account for the high ductility typical of metals. It is an historical irony that only in the past few years has fracture mechanics been concerned once again with brittle materials and attention has returned to the study of rock fracture. Although sixty years

Figure 1(a)

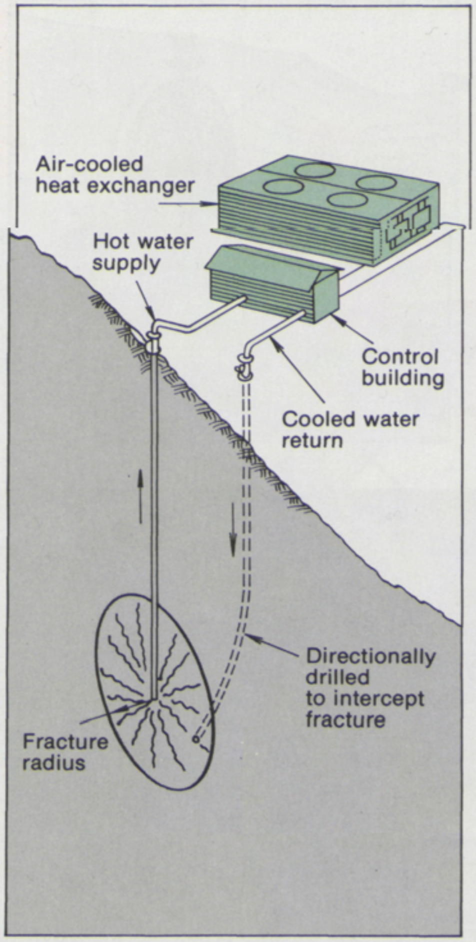
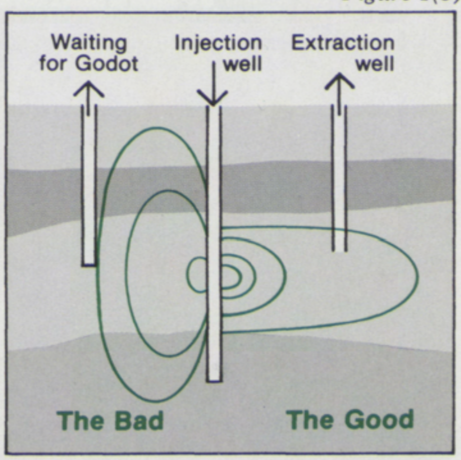



*Figure 1. The hot-dry-rock geothermal energy recovery method.*

*(a) Circulating water is heated by hot rock at variable depths in the Earth's crust. The rock is fractured to permit circulation and to expose large surface areas to the water flow.*

*(b) Success depends on the effectiveness of the rock fracturing. The location of injection and extraction wells is determined on the basis of knowledge of the fracture properties of the different rock layers — knowledge sought in rock mechanics research at Cornell.*

Figure 1(b)




in development, fracture mechanics is, in fact, a new tool for geotechnical engineers.

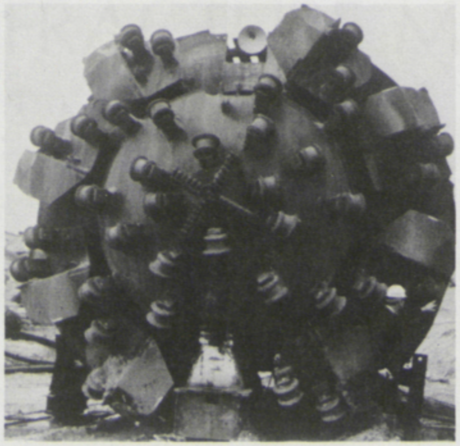
## CORNELL PROJECTS IN FRACTURE MECHANICS

Researchers at Cornell are studying the fracture mechanics of rock and its overlooked synthetic counterpart, massive concrete, on a wide structural scale and with a variety of practical applications in mind. Three examples of current projects will demonstrate the scope and suggest the value of this work.

A scheme for the recovery of energy resources (petroleum, natural gas, or even heat) by hydraulic fracture is illustrated in Figure 1. The purpose is to extract the resource material from a rock stratum by creating a large fracture surface area into which the material can flow for subsequent removal. This surface area is created by applying hydraulic pressure to a drill hole, thereby inducing a fracture plane which propagates through the stratum; a key requirement for efficiency is to keep the fracture plane in that stratum only.

The experimental work at Cornell is directed toward the study of a crack front approaching a material interface. Researchers hope to learn which material fracture parameters govern whether a crack will stop at an interface, cross it, or bend out of its plane to travel along the material interface. This study is expected to provide a means of determining which material property tests should be performed on core samples taken from the vicinity of an interface, and give a basis for interpreting and comparing the test results. Presumably the procedure could be used to decide the economic feasibility of hydrofracturing in the drill-hole location.

Rock-fracture problems on a smaller scale are involved with design of tunnel-boring machines (TBM's). These machines (see Figure 2) fracture rock with a series of disc cutters rolling under pressure across the rock face. Although TBM's operate successfully throughout the world on a wide variety of rock types, the actual mechanisms by which the cutters fracture rock is still little understood. Economic success with machine tunneling requires the highest

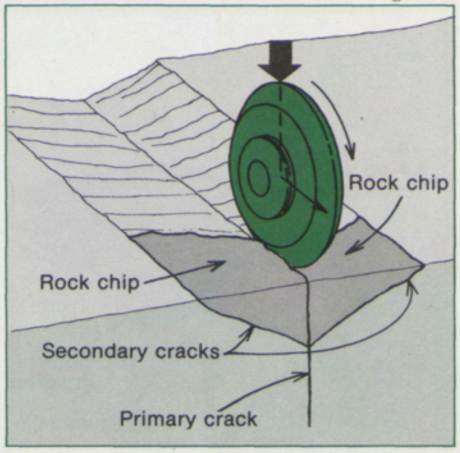


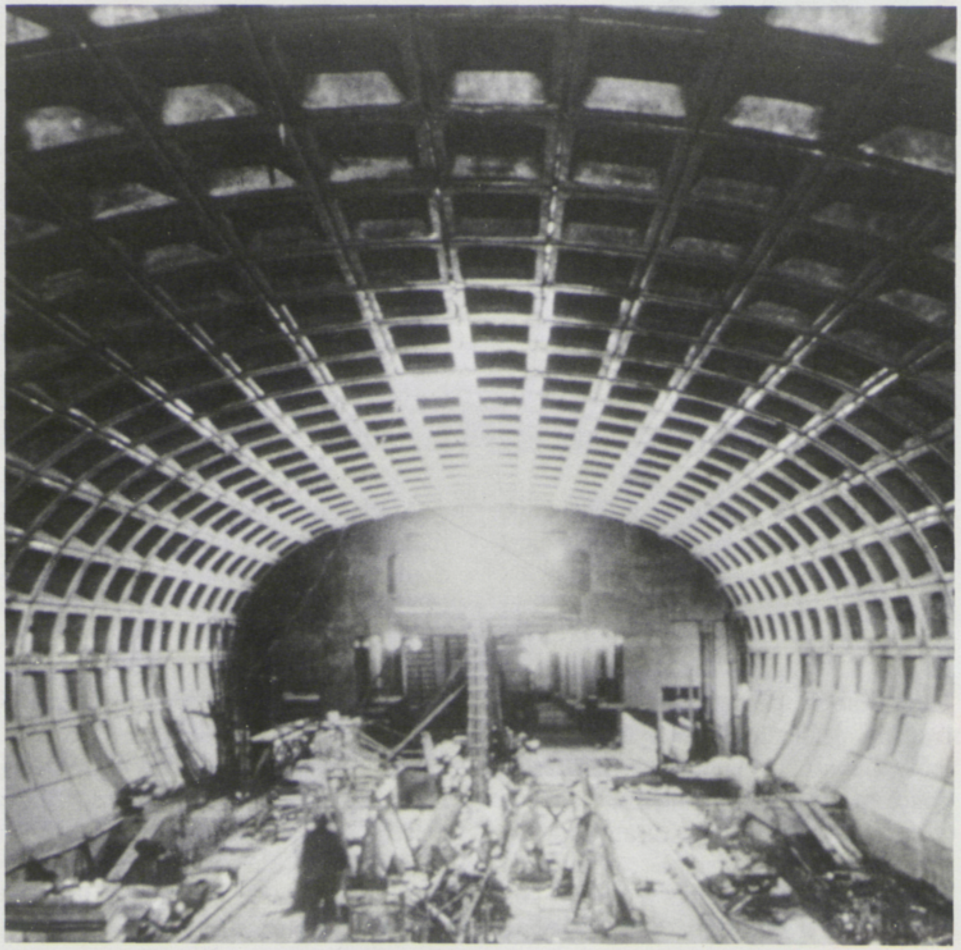
*Left: This large machine is used for boring tunnels in rock. The rollers carve the tunnel by chipping off rock fragments.*

*Right: The schematic in Figure 2 shows the action of an individual roller advancing across a rock face. Fracture is induced by a combination of the rolling motion and heavy pressure applied perpendicular to the rock face. The mechanism of the rock fracture is being studied at Cornell.*

*Below: A major application of tunnel-boring machines is in excavation for subway systems. This is a station of the Washington, D.C. metro during construction.*

*Figure 2*



penetration rate at the lowest machine cost. These variables are highly dependent on certain machine characteristics—thrust, horsepower, cutterhead rpm, number of cutters, and cutter geometry—and also on the fracture characteristics of the rock. Recent developments in fracture mechanics and finite element analysis are being applied in the research effort at Cornell to understand how application of a rolling compressive load can result in tensile fracture of rock. If the fracture mechanisms at work in a particular rock type can be fully understood, the cutter geometry and spacing can be adjusted for the greatest penetration rate with the least machine power requirement.

Research on fracture mechanisms in concrete, spurred by recent dam failures in the United States, can assist in the concentrated effort by various government agencies to examine the safety of existing dams and ensure fail-safe design on new dams. The Cornell group is engaged in pioneering efforts in the application of fracture mechanics concepts to the problem of cracking in monolithic concrete dams. Here the

*Figure 3*

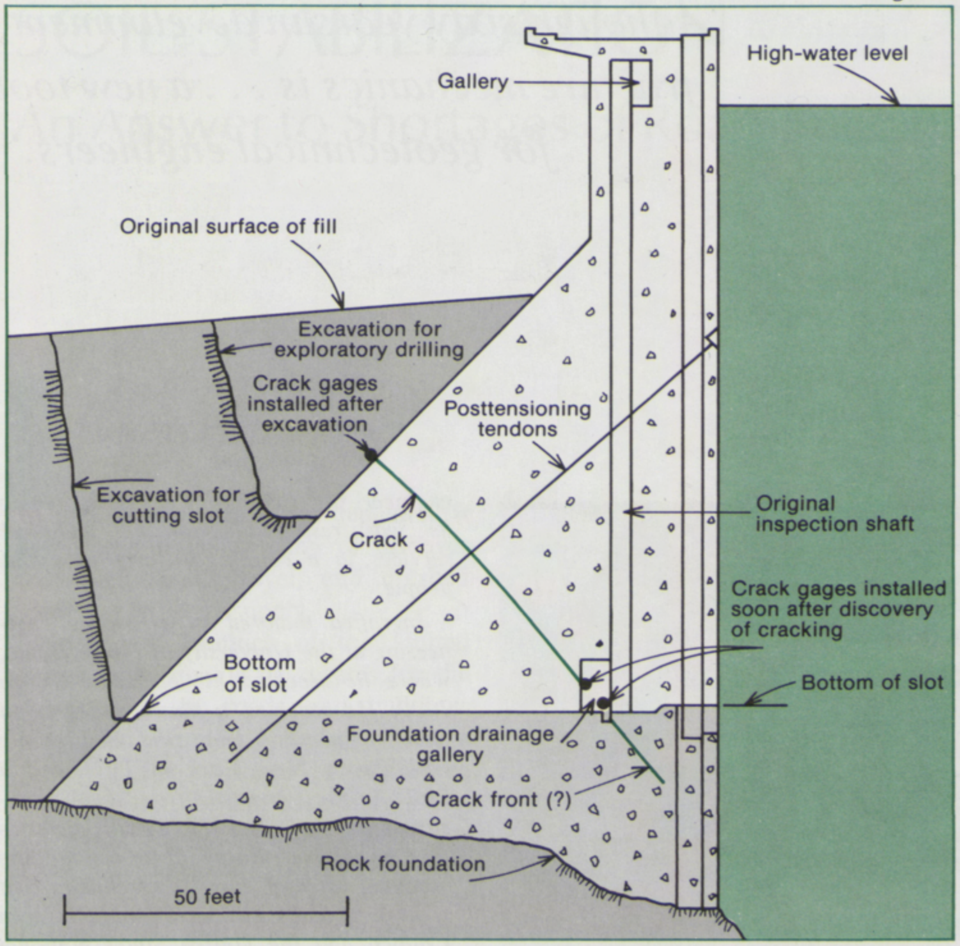
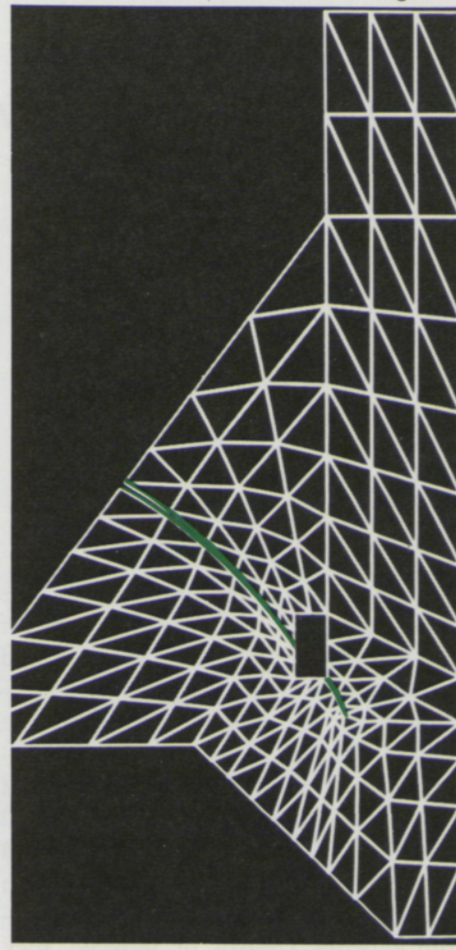



*Figure 4*



objectives are to ascertain the seriousness of cracks discovered in existing dams, and to explain these failures in order to avoid design errors in the future. A typical problem (see Figure 3) would be to increase the stability of a monolith in which a crack has been discovered. The analytical methods being developed would help the engineer to learn the cause of the crack, model its known trajectory, locate the crack front, and choose the most effective methods of reinforcing the monolith and halting crack growth.

*Figure 3. Attempted repair of a crack in a large dam. The crack was detected during inspection from the drainage gallery, and subsequent excavation of the fill revealed the origin of the crack on the downstream face. Unsuccessful attempted fixes included installation of posttensioning tendons and pressure grouting of the crack. The final fix involved cutting a transverse slot across the dam to isolate the damaged monoliths from the forces driving the crack. In effect, this "cut" the dam into several sections, separated by an impermeable seal. Determination of the present location of the crack front, however, as well as more general matters such as the predicted effectiveness of attempted fixes and the actual mechanisms of crack initiation and propagation require more research such as the ongoing work at Cornell.*

*Figure 4. Finite element analysis is one of the techniques being used to study the propagation of cracks in large dams. This figure shows a finite element mesh of a dam such as the one illustrated in Figure 3. Application of fracture mechanics principles allows the prediction of the crack trajectory (such as the one shown in color) as a function of applied loads.*

*"Although sixty years in development, fracture mechanics is . . . a new tool for geotechnical engineers."*

## MEETING THE DEMANDS OF WORK WITH ROCK

Although the application of fracture mechanics methodologies to problems such as these is still in its research and development stage, the practical objectives and their pressing importance are clear. Efficient processes for the extraction of geothermal energy and of untapped reserves of petroleum and natural gas, as well as energy-related technologies such as in-situ gasification of coal and oil-shale retorting, will require better control of induced rock fracture. Any plan for storing nuclear and chemical wastes in geological formations will demand an understanding of rock fracture in thermal and corrosive environments. The economic feasibility of large-scale underground transit systems may depend on the efficiency of tunnel-boring machines.

Fracture mechanics is ideally matched against these and other challenges of energy development and structural reliability. It provides a versatile and powerful tool for the geotechnical engineer.

*Anthony R. Ingraffea, an assistant professor in Cornell's Department of Structural Engineering since 1977, has followed his concern with fracture mechanics through a variety of applications: he worked at the Grumman Aerospace Corporation on preliminary designs for the Navy F-14 aircraft and on final design of a NASA space shuttle proposal; and he has done research under a Bureau of Mines contract on constitutive relations of coal and coal-measured rock. Between these extremes of altitude, he served for two years in the Peace Corps as county engineer for Bejuma, Venezuela, where he was responsible for all technical services in a county of forty thousand people.*

*Ingraffea majored in aerospace engineering at the University of Notre Dame, where he received his baccalaureate in 1969. He received a master's degree in civil engineering from the Polytechnic Institute of New York in 1971 and a Ph.D. in the same field from the University of Colorado in 1977. For his dissertation, he received the award for outstanding graduate research in rock mechanics that is given annually by the National Research Council and the United States National Committee for Rock Mechanics.*

*At Cornell his teaching and research interests center on fracture mechanics, including mechanical modeling and testing of rock and concrete fracture, as well as general structural mechanics. This spring he was chosen for the Tau Beta Pi–Cornell Society of Engineers Excellence in Teaching Award. Last year the Cornell chapter of Chi Epsilon selected him for its Professor of the Year Award.*

*He is a member of the American Society of Civil Engineers, the American Society for Testing and Materials, and the Society for Experimental Stress Analysis, and is a licensed professional engineer in Colorado.*

# SOIL STABILIZATION

## An Answer to Shortages of Road-Building Materials

*by Lynne H. Irwin*

In these times of resource depletion, it is perhaps not surprising to discover that even sand, gravel, and crushed stone are in short supply.

In many localities of the United States, good-quality aggregates for the construction of roads and buildings have been completely used up. Even in some of the northern states, where glaciation left behind seemingly abundant supplies of aggregates, there are local shortages. In Rochester, New York, for example, the closest source of processed gravel for a reconstruction project at the airport is a thirty-minute haul away, and the second closest supply is an hour away. Because of high prices for trucks, labor, and fuel, such hauls add significantly to the cost of construction. And, of course, in areas in which supplies are limited, the cost of the material itself has gone up rapidly, further escalating construction costs.

One of the immediate results, directly evident to taxpayers, is increased expense for maintaining local roads. Many governments at the county, town, city, and village levels are faced with the need to rebuild roads that have come to the end of their useful life. If they attempt to reduce costs by using lower-quality materials, durability will probably be sacrificed, and the result will be high cost in the long run.

This dilemma has been tackled by our Local Roads Program at Cornell. Through research and extension efforts, we are seeking to improve the quality of locally available aggregates to permit low-cost, durable road construction. The technique that is being investigated is soil stabilization, a means of increasing the strength of materials through compaction or the addition of small amounts of cementing agents.

### WHY GOOD AGGREGATES ARE HARD TO GET

The actual consumption of available good-quality aggregates in the building of the nation's cities, and their streets and highways, is part of the reason for shortages of these materials. A second factor is that the number of available sources has diminished as a result of the growth of residential areas and the enactment of laws to protect the environment.

When a new neighborhood develops at the edge of a city, a frequent consequence is the closing of a gravel pit. Noise and dust emanating from the plant bring legal action from residents, and the owners of the business often find it less expensive to relocate than to clean up. Property taxes, based on "highest use," may also make relocation attractive. Other closures are the result of legislation for environmental protection. Laws prohibiting the removal of gravel from stream beds are now common in most states; the aim is to protect against the downstream discharge of silt, which disrupts the habitat for fish, inhibits spawning, and lowers water quality. Many states also have laws mandating clean rivers, clean air, pure waters, and mined-land reclamation. The reclamation laws have especially affected low-production sources of quality aggregates because the cost of filing a comprehensive plan for reclamation is prohibitive when gravel sales are only incidental. Both publicly-owned and privately-owned aggregate sources have been closed as a result of such a law in New York.

The key to an understanding of these supply problems is an appreciation of the need for *good-quality* materials. Builders have learned from experience that durable products require aggregates that meet specific standards. In the base course of a road, for example, the presence of small amounts of silt and clay renders the material susceptible to frost heave if water is abundant in the area and ground freezing to significant depths is common. In such regions, an inadequate base course means a rough ride in the winter and a weak, potholed road in the spring. The problem is that even though there may be plenty of aggregate material available locally, it may not be of sufficiently high quality for the intended use. In New York State, for instance, there are still tremendous surface deposits of glacial debris, but much of this material has a high percentage of silt and clay, or it has shale particles, the size of sand grains, that will turn into silt and clay after a few seasons of repeated freezing and thawing on a road surface.

**RECOMMENDATIONS FOR ROAD GRAVELS**

| | Surface | Base |
|---|---|---|
| **Gradation** | | |
| % Gravel[1] | 50–70 | 50–70 |
| % Sand[2] | 25–40 | 25–40 |
| % Silt and Clay[3] | 8–15 | 0–10 |
| **Plasticity** | | |
| Plasticity Index | 2–5 | 0–2 |
| Sand Equivalent | 30 (min.) | 45 (min.) |

[1]Retained on a No. 10 sieve
[2]Passing a No. 10 and retained on a No. 200 sieve
[3]Passing a No. 200 sieve

## MATERIALS PROBLEMS IN RESURFACING ROADS

A frequent problem encountered by local governments in northern climates is how to upgrade existing gravel roads. When an impervious all-weather surface, such as asphalt, is applied over an otherwise satisfactory gravel surface, excessive distress and premature failure of the new surface is apt to occur. The reason for the poor results is apparent from the data in the table, which compares the recommended specifications for base-course aggregates with those for unstabilized road surfacing. The difference is in the recommended percentages of silt and clay and, as a result, in the degree of plasticity exhibited by the material. Although there is a slight overlap in the gradation specifications, it seldom happens that a material satisfies the criteria for both a surface and a base.

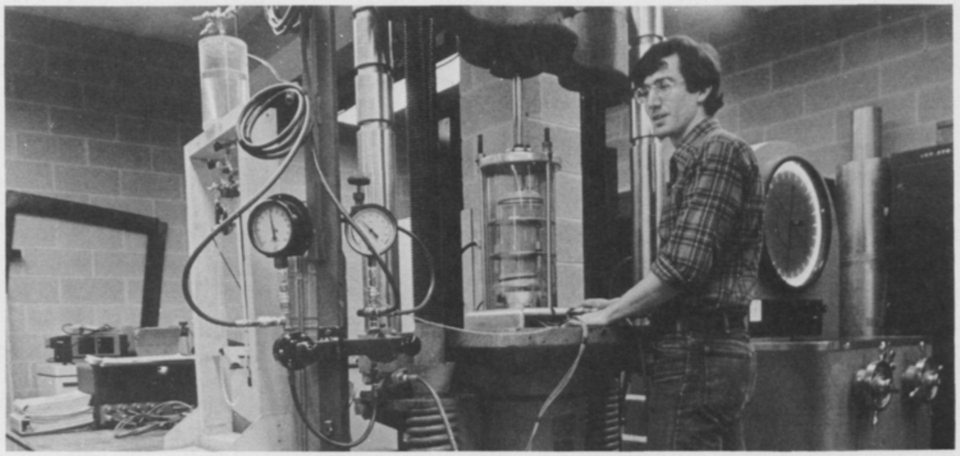
What do these specifications mean in terms of road performance? Some silt and clay, and some plasticity, are desirable in surface materials in order to prevent vehicle tires from rolling the coarser particles off the road and into the ditch. However, when the escape of capillary moisture is cut off by the addition of an impervious layer, the increased moisture content causes such gravel to soften. The road is weakened and the new surface, if it is too thin, will break up. What is needed is a cleaner, less plastic base material that will provide adequate shear resistance.

If a gravel road has been performing satisfactorily, this implies that it has met the gradation requirements for surface courses. But it also implies that the old road will not make a good base for blacktopping. One might hope that the failure to recognize that a good gravel surface makes a poor base would be a rare occurrence among road builders. Unfortunately, it is not. Such errors are repeated time and again, sometimes by the same officials.

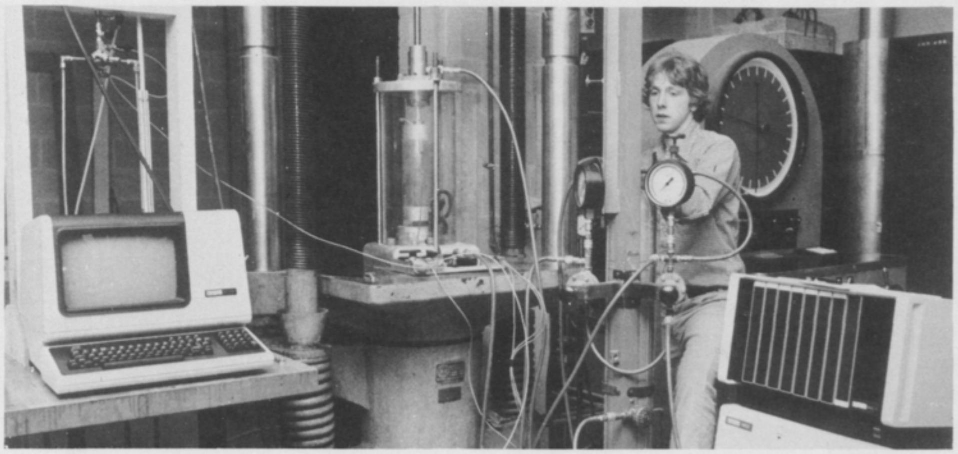
A solution to these problems in blacktopping gravel roads is to first stabilize the existing surface. This can be accomplished by applying appropriate chemicals, mixing in place, and compacting the resulting material before the blacktop is added. A superior road base is created and a long-lasting road improvement is the result. The cost of the base stabilization is more than offset by the increased longevity of the surface.

## THE MEANS OF ACHIEVING SOIL STABILIZATION

Mechanical stabilization can be achieved through compaction, or by improving particle interlock by blending together materials of different grain sizes. Of particular interest, however, is chemical stabilization, in which small quantities of chemical admixtures, such



1



2

as portland cement, lime, lime and fly ash, asphalt, sodium or calcium chloride, and resins, impart increased strength by causing the individual grains of the aggregate to adhere to each other. Chemical stabilization processes always involve compaction as well, and occasionally aggregates are blended before or during the addition of chemicals.

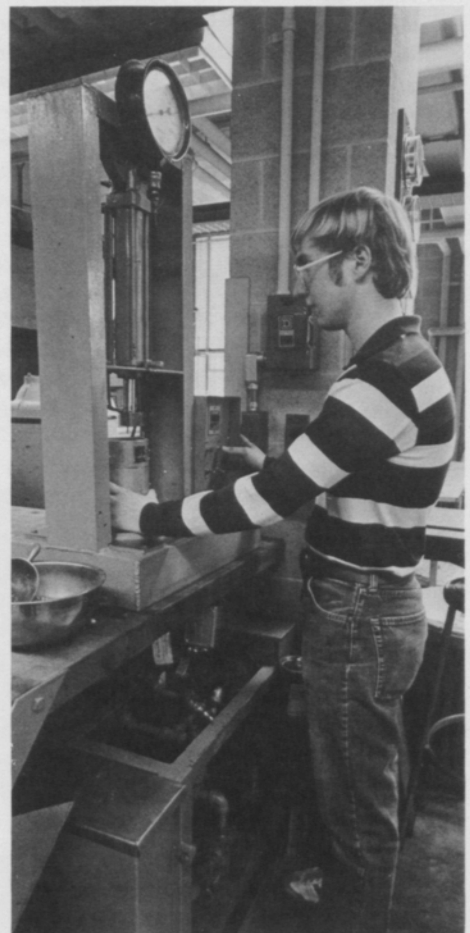
There are problems associated with the use of soil stabilization, however. One is that it can be difficult to decide on the kind and quantity of stabilizer

*1. Laboratory test facilities for the Cornell soil stabilization research include a sensitive and highly accurate triaxial apparatus developed for the project. Graduate student Glenn Hough performs a test on a compacted specimen to determine how the stabilizers work to strengthen the soil.*

*2. Data from each triaxial test is continuously monitored by a new laboratory computer, the first of its kind on the Cornell campus. Graduate student Bill Walton is shown preparing to make a test.*

*3. A low-cost hydraulic kneading compactor was designed and built for the project to simulate field compaction conditions. Here senior agricultural engineering student Steve Delwiche fabricates stabilized test specimens for triaxial testing. Seven undergraduate engineering students have been employed in the project.*

3



*Cornell research on soil stabilization techniques includes field studies near the campus to assess the longevity and environmental impacts of chloride stabilization.*

*1. Liquid or solid sodium chloride or calcium chloride is spread on the surface of a gravel road and subsequently mixed and compacted.*

*2. Local highway officials collaborated in construction for the project. Strips built for demonstrations during annual conferences for county and town superintendents (sponsored by the Cornell Local Roads Program) often have served subsequently as test roads.*

*3. Road dust is a costly commodity; Cornell engineers have determined that an unstabilized surface loses about one ton of gravel per mile each year. The annual cost of replacement is estimated as between $6 million and $15 million in New York State alone. Chloride stabilization helps to control these losses from gravel surfaces.*

*4. Senior civil engineering students Valerie Wimer and Tom Faraone obtain samples for determinations of density and chloride content. It was found that about half the chloride is gone after one month, although the beneficial effect of dust control is measurable for nearly two months.*

*1*

*2*

*3*

*4*

*" . . . an inadequate base course means a rough ride in winter and a weak, potholed road in the spring."*

to use with a given aggregate. Various test methods have been developed by industrial groups over the years, but they all have limited applicability. If lime is to be used, for example, the mix proportions are determined on the basis of measurements of compressive strength. For stabilization with cement, a lengthy freeze-thaw test must be performed. For stabilization with asphalt, a different set of tests is specified. Many highway agencies become frustrated by the diverse, slow, expensive testing that must be done, and instead continue to use the sometimes inappropriate construction methods they are familiar with. What they need is a simplified, general method for determining which and how much stabilizer to use—a design procedure such as the one we are developing as a long-term project in the Local Roads Program.

## THE CORNELL PROJECT AND ITS SIGNIFICANCE

Research on soil stabilization must begin with the study of how various stabilizers work: the first criterion for any test procedure is that it must measure the appropriate properties. But despite the fact that some chemicals have been in use for as long as fifty years, the understanding of how they develop strength in the road material is very poor.

The Cornell project is developing in several phases. The first is the development of equipment and instrumentation needed for precise measurement of the behavior of stabilized soils under load. The second is the definition of suitable failure criteria for stabilized soils. Phase 3 is a study of the influence of the various types of stabilizer on the strength properties of road materials. The final step is to specify simple test procedures that will permit a determination of the kind and quantity of stabilizer needed.

These four phases of the project are not completely independent of each other, since the developments in one influence the directions taken in the others. Phase 1, equipment and instrumentation development, has progressed the most. Some of these developments were described in an earlier article in *Engineering: Cornell Quarterly* (vol. 11, no. 4, winter 1977). Since that time, a highly instrumented triaxial cell has been built for measuring the cohesive and frictional properties of compacted stabilized materials. A small laboratory computer, just received, will greatly speed up the acquisition, processing, and interpretation of data from the instruments. Work is also moving forward on Phases 2 and 3; a number of geotechnical engineering graduate students are involved in these aspects of the project.

Field studies, as well as laboratory experiments, are a necessary part of the project research. For several years, for example, test roads constructed of materials stabilized with sodium chloride or calcium chloride have been examined for changes in surface density and for retention of these highly soluble chemicals. It has been found that the movement of chlorides is controlled by the capillary rise of moisture through the surface. Although Ithaca had the wettest year on record two years ago, rainfall infiltration was found to have no significant effect on the rate of chloride removal.

Much remains to be learned about the strength properties of stabilized soils. Of particular interest will be the seasonal changes in roads built with these materials, as compared to roads built with conventional unstabilized aggregates. In northern climates, winter frost heave followed by spring thaw can in some years have a drastic effect on the performance and riding quality of roads. Potholes cost money to repair, and they often cause expensive vehicle damage as well. Stabilized materials seem to be better able to resist the seasonal changes, and this needs further study. Equipment will have to be purchased or developed in order to pursue this line of investigation, however, and at the present time the research funds are too limited to allow this.

The Cornell project has the dual aim of finding out more about how to use soil stabilization techniques and of making them readily accessible. Under present circumstances, highway officials are reluctant to try the new methods; even if they were convinced of the effectiveness of stabilized materials, they would have difficulty deciding how much of what to add to a particular aggregate for a given job. Yet the current problems of maintaining and upgrading low-volume roads can only get worse as good-quality aggregates become harder to obtain. For these reasons, the work of Cornell engineers in developing a practical analytic and design method, and in making the information available to engineers in the field, is important and timely. With correct treatment, even poorer-quality materials can provide good, long-lasting surfaces for the nation's local roads.

---

*Lynne H. Irwin, associate professor of agricultural engineering, is the leader of the Cornell Local Roads Program. He indicates that although low-volume roads constitute about 80 percent of the 3.8 million miles of road in the United States, Cornell, out of all the universities in the country, has the only program that is devoted exclusively to improving the engineering of such roads.*

*Irwin received the B.S. and M.S. degrees in civil engineering from the University of California at Berkeley in 1965 and 1966, respectively. In 1973 he was granted the Ph.D. degree by Texas A&M University, where he studied problems of road materials and pavement engineering. Before joining the Cornell faculty in 1973, he taught for three years in civil engineering at California State University at Chico. He has worked for a construction firm and for a consulting engineering laboratory in California, and he has also had experience as a consultant and expert witness on problems of highway engineering and pavement design. He is a licensed professional engineer in Texas.*

*Irwin is a member of the American Society of Civil Engineers and the American Society of Agricultural Engineers, and serves as vice president of the Educational Division of the American Road and Transportation Builder's Association. He is a member of the Transportation Research Board of the National Academy of Sciences, and serves on the board's committees on low-volume roads, theory of pavement design, and soil-cement stabilization. He is also a member of the Transportation Research Board's steering committee for a project on transportation technology support for developing nations.*

# THE SHAPING OF A DISCIPLINE

*by Thomas D. O'Rourke*

In 1935, when damaging floods focused attention on the problems of flood control, the study of soil mechanics had just been introduced at Cornell. Then, after the water had receded, the United States Army Corps of Engineers set up a regional flood-control headquarters in nearby Binghamton and, as part of the operation, built a soil mechanics laboratory on the Cornell campus. One result was a fruitful collaboration by University and Corps researchers: fundamental work on shear and compression properties of soil and studies of permeability and embankment stability in earth dams were accomplished at the new laboratory. In addition, the flood-control activity provided an impetus to the early development of what became the area of geotechnical engineering at Cornell.

The entire history of geotechnical engineering at Cornell is, in fact, a microcosm of the field at large as it developed in response to changing needs and attitudes. Here at the University, as throughout the country, the early interest in soils and foundation behavior broadened to include other aspects of geology and earth structures. Ultimately, geotechnical engineering emerged as a well-defined speciality.

## THE SEMINAL YEARS UNDER S. C. HOLLISTER

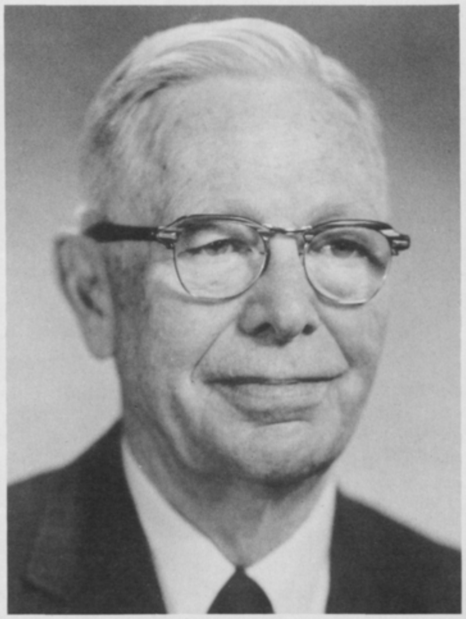
At Cornell the growth of the discipline in the mid-1930's was owing in large part to the leadership of S. C. Hollister, who served as director of the School of Civil Engineering from 1934 until he became dean of the College three years later. It was on Hollister's instigation that instruction in soil mechanics was added to the curriculum: in 1935 Herbert T. Jenkins was appointed as an assistant professor to teach the new subject along with the established course in engineering drawing. And it was Hollister who invited the Corps of Engineers to build its laboratory at Cornell (it was located on Tower Road, just east of the intersection with Judd Falls Road). The collaboration extended to the academic as well as the research program; for example, Benjamin K. Hough, the head of the government laboratory, was provided with a room in Lincoln Hall on the campus and in 1940 was appointed a special lecturer in soil mechanics at the graduate level. Later he joined the regular faculty.

Jenkins and Hough were among the delegates to the First International Conference on Soil Mechanics and Foundation Engineering that convened in 1936 in response to the heightened interest in these subjects. Jenkins contributed a short paper in which he described the program at Cornell:

> Sufficient equipment for making routine tests is available to eight men at a time, and the laboratory sections are limited to that number. Thus, the determination of specific gravity, moisture content, void ratio, moisture equivalent, mechanical analysis, and Atterberg limit tests are made by each student. The larger experiments on the physical and mechanical properties of soil, such as tests for shearing strength, compressibility, and permeability are performed by the class as a whole. All such work is coordinated with lectures given in the Soil Mechanics course.

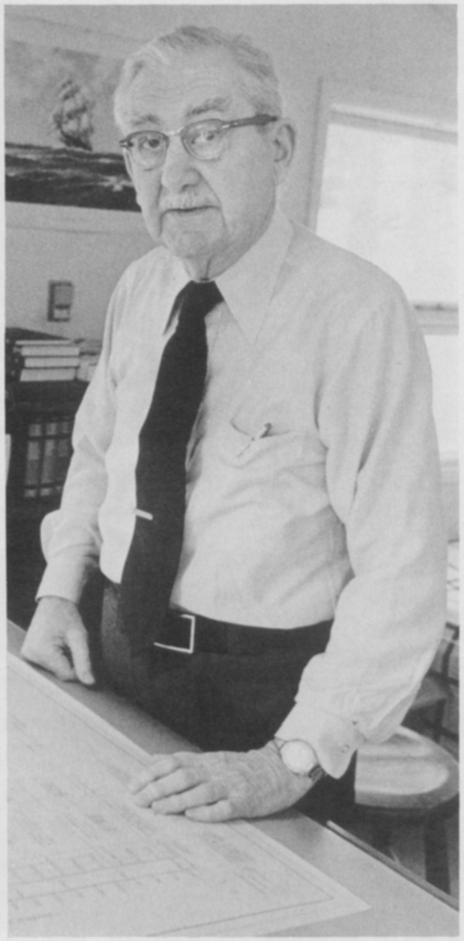
*This historic photograph was taken at the First International Conference on Soil Mechanics and Foundation Engineering, which convened at Harvard University in 1936. Delegates from Cornell included Benjamin K. Hough (standing in the third row, sixth from the left) and Herbert T. Jenkins (sitting at the right end of the second row). Jorj O. Osterberg, who earned Cornell's first Ph.D. degree in soil mechanics four years later, was also present. The president of the conference, Karl Terzaghi (known as the father of modern soil mechanics), is standing, second from the left side. Arthur Casagrande, a major contributor to the study and practice of geotechnical engineering and professor at Harvard since 1934, is behind Terzaghi, at the end of the row.*

*Hollister*



*S. C. Hollister, who was dean of the Cornell College of Engineering for twenty-two years during its period of greatest growth, initiated instruction in soil mechanics in 1935 during a preceding term as director of the School of Civil Engineering. He retired in 1959 but still maintains an office in Hollister Hall, the civil and environmental engineering building named in his honor.*

*Hough*



*Benjamin K. Hough, an important figure in the early history of geotechnical engineering at Cornell, retired in 1957 and is now a private consultant in Ithaca. Currently he is also working on the third edition of his book,* Basic Soils Engineering, *which was first published in 1957 and has become a standard text.*

*The first recipient of a Cornell Ph.D. in soil mechanics was Jorj O. Osterberg, now the Walter P. Murphy Professor of Civil Engineering at Northwestern University and a member of the National Academy of Engineering. At Cornell he did his thesis research on soil pressure cells and then went to work at the Waterways Experiment Station in Vicksburg, Mississippi, where he was instrumental in the design and building of a soil stress cell for the Corps of Engineers. He joined the Northwestern faculty in 1943, after a year at the University of Illinois. Osterberg is probably most widely known as the developer of the Osterberg sampler, a device for taking undisturbed soil samples.*

*Osterberg*

The first Ph.D. in soil mechanics at Cornell was awarded in 1940 to Jorj O. Osterberg, a McMullen Research Scholar, whose thesis was on soil pressure cells. Osterberg is now a chaired professor at Northwestern University.

## THE WAR AND POSTWAR PERIODS OF DEVELOPMENT

World War II collaboration led to a Cornell connection that played an important role in the shaping of the geotechnical engineering program here. As an Army officer, Hough was stationed in Kunming, China, and as part of a mission to supply and train Chinese troops, worked with a Chinese liaison engineer named Ta Liang. After the war, Liang came to Cornell as a graduate student, worked with the newly appointed Professor Donald J. Belcher and, after receiving his doctorate in 1952, remained as a member of the faculty. Over a period of many years, Belcher and Liang cooperated in developing a pioneering program of study and research that has gained international recognition. As a new faculty

*Cornell Professors Donald J. Belcher (at left) and Ta Liang pioneered in the use of remote sensing techniques in geotechnical and other engineering applications, and have participated in engineering projects all over the world. Belcher, who became an emeritus professor in 1976, is still active as a private consultant. For many years he served as director of the University's widely recognized Center for Aerial Photographic Studies. Among his achievements were the siting of Brasilia, the capital of Brazil, and the siting of the world's largest radio-radar telescope at Arecibo, Puerto Rico. Liang served as director of Cornell's Tropical Soils Airphoto Research Project and is now head of the Program in Environmental Sensing, Measurement, and Evaluation at the School of Civil and Environmental Engineering.*

member, Belcher introduced his specialty of airphoto interpretation and remote sensing and built a strong capability in this area at Cornell. As a graduate student, Liang applied these techniques to problems of landslide detection and control, an area in which he had become interested during his wartime experience with landslides along the Burma Road. These two men initiated and directed projects all over the world on the siting of engineering facilities such as roads, bridges, dams, and even cities, the location of mineral resources, and the analysis and planning of land usage. This work continues today, and the cooperation between the Cornell groups in environmental sensing and in geotechnical engineering provides exceptional opportunities for research and study.

Another development during the postwar period was the disbanding of the Corps of Engineers laboratory and the incorporation of parts of it into a Cornell facility. Under the direction of Hough—by then a member of the University faculty—the laboratory was organized into self-contained units that permitted small groups of students to work on experiments. Classes numbering twenty-five to thirty members received instruction in the expanding field of geotechnical engineering. One of the projects undertaken at this laboratory was an extensive program of research into the fundamental properties of clay-water systems. The project, funded by the Corps of Engineers and directed by Hough, had its origin in the problems of military transportation on low-grade roads during the war, but

also had application to peacetime transportation in many parts of the world. The research effort drew heavily on expertise in other fields at Cornell; staff members from the Departments of Agronomy, Chemistry, Physics, and Engineering Physics participated.

*Geotechnical engineering professors Mel Esrig (near the center) and David Henkel (right center) maintained close contact with students. On late Friday afternoons they frequently met with graduate students at the "Palms" in Collegetown, near the campus, for informal discussions.*

## NEW STRENGTH IN THE DEPARTMENT

In the 1950's and 1960's geotechnical engineering at Cornell continued to grow substantially in size and scope.

Bengt Broms, who arrived in 1958 with a doctorate from the University of Texas, was a specialist in the behavior of reinforced concrete structures and directed important research on soil-structure interaction and the cracking of reinforced concrete beams. He also worked on the shear strength and deformation properties of clay, and his publications on the lateral resistance of piles in cohesive and cohesionless soils are basic references on the subject. In 1964 he left Cornell to become the director of the Swedish Geotechnical Institute.

Melvin I. Esrig, who joined the faculty in 1962, and David J. Henkel, who came in 1965 as head of the geotechnical engineering group, introduced new research activities and greatly expanded the course offerings. Esrig's work included studies of the shearing resistance of soil and of electrokinetic processes in soil. Henkel continued his already established research program in shear strength and stress path analysis of clay. He also developed techniques for analyzing slope stability and laid the theoretical groundwork for studies of the effect of wave motion on submarine slope stability. Esrig is now a principal of Woodward Clyde Consultants, Clifton, New Jersey, and Henkel is head of the geotechnical division at Ove Arup and Partners of London and a director of the firm.

*"... cooperation ... in environmental sensing and in geotechnical engineering provides exceptional opportunities . . ."*

*Cornell equipment for research in geotechnical engineering includes this Anteus apparatus for measuring one-dimensional consolidation of clay and pore pressure. These tests are useful for evaluations such as the amount of settlement to be expected under a structure or the predicted behavior of earth dams. The researcher is Harcharan Singh, who received a Ph.D. in 1971 and is now a partner of Dames and Moore, consultants, in Washington, D.C.*

Visiting professors who contributed to the department activities during this period were Gregory P. Tschebotarioff, a specialist in foundation engineering from Princeton University, and C. Peter Wroth, an authority on stress and failure states in soils, who was on leave from Cambridge University.

## RECENT DEVELOPMENTS IN THE CORNELL PROGRAM

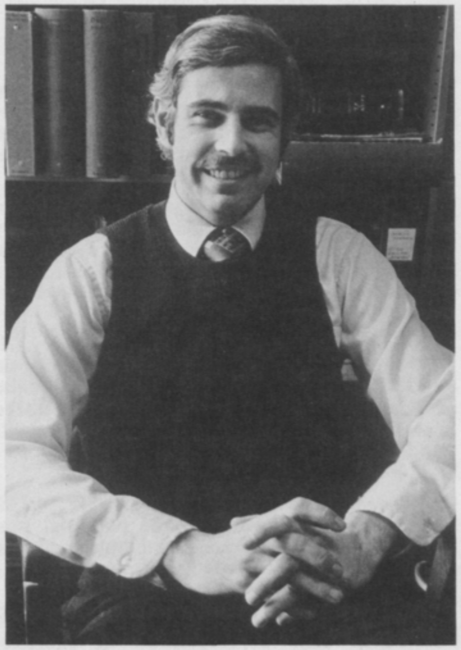
During the current decade, a number of distinguished engineers and teachers have contributed to the program. J. Neil Kay, for example, developed statistical methods for judging the structural integrity of cellular cofferdams while he was at Cornell as an assistant professor. Among those who came as visiting professors or lecturers or as consultants for the Master of Engineering design projects are Richard E. Goodman, professor at the University of California at Berkeley (see his article in this issue); Roland W. Lewis, lecturer at the University of Wales; Don Rose of the Tudor Engineering Company; Charles A. Moore, professor at Ohio State University; Joseph A. Fischer, partner at Dames and Moore; Bill T. D. Lu, senior engineer at Dames and Moore; and Peter J. Tarkoy, consultant to the Perini Corporation.

Present members of the geotechnical engineering group, which is part of the Department of Structural Engineering, are Dwight A. Sangrey, Fred H. Kulhawy, and Thomas D. O'Rourke. Together with colleagues in other academic areas whose fields of expertise complement the work of geotechnical engineers, all are represented by articles in this issue of the *Quarterly*.

*"The entire history of geotechnical engineering at Cornell is . . . a microcosm of the field at large "*

The Cornell program has grown to accommodate the current wide range of interests and needs of geotechnical engineering. Undergraduate and graduate courses are offered in soil mechanics, soil dynamics, the engineering properties of soils, foundation engineering, rock engineering, earth-retaining structures and slope stability, embankment dam engineering, and tunnel design and construction, in addition to laboratory techniques and case studies of geotechnical projects. The laboratory facilities have expanded to cover a broad range of tests: index, triaxial, cyclic loading, dynamic loading, hollow cylinder, and plane strain. Additional equipment provides capabilities for direct shear measurements, one-dimensional consolidation testing with pore pressure measurements, rock testing, electronic monitoring with 24-channel analog recording, and large-scale foundation modeling. Graduate students majoring in geotechnical engineering have increased from one or two a year in the early 1950's to the current group of twenty-one.

Forty-four years after its inception, geotechnical engineering at Cornell continues to have a strong program of teaching and research that is both responsive to industry and makes a notable contribution to state-of-the-art developments.



*Thomas D. O'Rourke, a 1970 Cornell graduate in civil engineering, returned to the University as an assistant professor last year. He did his graduate work at the University of Illinois, which awarded him the M.S. degree in 1973 and the Ph.D. in 1975, both in geotechnical engineering.*

*In 1976 he received the C. A. Hogentogler Award of the American Society for Testing and Materials. During 1976–77, he worked in the United Kingdom as a representative of the United States Department of Transportation in a research and development program with the British Transport and Road Research Laboratory.*

*O'Rourke's teaching and research interests extend to geotechnical instrumentation and analytical methods, but he is primarily interested in underground construction and soil-structure interaction. Since his arrival at Cornell, he has completed a state-of-the-art report on underground construction methods and systems in Europe, and has started sponsored research on the behavior of buried pipelines crossing active fault zones.*

*He is an associate member of the American Society of Civil Engineers and a member of the National Society of Professional Engineers and the International Society of Soil Mechanics and Foundation Engineering.*

# FACULTY PUBLICATIONS

*The following publications and conference papers by faculty and staff members and graduate students of the Cornell University College of Engineering were published or presented during the period September through November 1978. Earlier entries inadvertently omitted from previous listings are included here in parentheses. The names of Cornell personnel are in italics.*

## ■ AGRICULTURAL ENGINEERING

*Albright, L. D.* (1978). Air flow through baffled, center-ceiling, slotted inlets. *Transactions of the ASAE* 21 (4):944–947.

*Davis, H. R.; Isenberg, F. M. R.; and Furry, R. B.* 1978. *The control of natural-air cabbage storage environment.* Plant Sciences–Agricultural Engineering information bulletin no. 137. Ithaca, N.Y.: New York State College of Agriculture and Life Sciences, Cornell University.

*Millier, W. F.; Rehkugler, G. E.; Pellerin, R. A.;* and *Throop, J. A.* 1978. *High capacity harvesting apparatus.* United States patent no. 2,121,407, issued 24 October 1978.

*Srivastava, A. K.; Rehkugler, G. E.;* and *Masemore, B. J.* (1978). Similitude modeling applied to ROPS testing. *Transactions of the ASAE* 21(4):633–645.

*Timmons, M. B.,* and *Albright, L. D.* 1978. Wind directional dependence of sol-air temperatures. *Transactions of the ASAE* 21(5): 742–746.

*Timmons, M. B.; Albright, L. D.;* and *Furry, R. B.* (1978). Similitude aspects of predicting building thermal behavior. *Transactions of the ASAE* 21(4):956–962.

## ■ APPLIED AND ENGINEERING PHYSICS

*Axelrod, D.; Wight, A.; Webb, W. W.;* and *Horwitz, A.* (1978). Influence of membrane lipids on acetylcholine receptor and lipid probe diffusion in cultured myotube membrane. *Biochemistry* 17:3604–3609.

*Cookingham, R.,* and *Lewis, A.* 1978. Resonance Raman spectroscopy of chemically modified retinals: assigning the carbonmethyl vibrations in the resonance Raman spectrum of rhodopsin. *Journal of Molecular Biology* 119:569–577.

*Cookingham, R.; Lewis, A.;* and *Lemley, A.* 1978. A vibrational analysis of rhodopsin and bacteriorhodopsin chromophore analogues: resonance Raman and infrared spectroscopy of chemically modified retinals and Schiff bases. *Biochemistry* 17:4699–4711.

*Dragsten, P. R.,* and *Webb, W. W.* 1978. Mechanism of the membrane potential sensitivity of the fluorescent membrane probe merocyanine 540. *Biochemistry* 17:5228–5240.

*Ehrenberg, B.,* and *Lewis, A.* 1978. The pK of Schiff base deprotonation in bacteriorhodopsin. *Biochemical and Biophysical Research Communications* 82:1154–1159.

Ippen, E.; Shank, C. V.; *Lewis, A.;* and *Marcus, M.* 1978. Subpicosecond spectroscopy of bacteriohodopsin. *Science* 200:1279–1281.

*Lewis, A.* 1978. The molecular mechanism of excitation in visual transduction and bacteriorhodopsin. *Proceedings of the National Academy of Sciences* 75:549–553.

———. 1978. The structure of the retinylidene chromophore in bathorhodopsin. *Biophysical Journal* 24:249–254.

———. (1978). Tunable Laser Spectroscopy: a Probe of the Molecular Mechanism of Excitation in Visual Transduction. Plenary lecture delivered at Meeting of Royal Society of London, 22 February 1978, in London, England.

*Lewis, A.; Marcus, M. A.; Ehrenberg, B.;* and Crespi, H. 1978. Experimental evidence for secondary protein-chromophore interactions at the Schiff base in bacteriorhodopsin: a molecular mechanism for proton pumping. *Proceedings of the National Academy of Sciences* 75:4642–4646.

*Liboff, R. L.* 1978. Hydroelectric solar energy conversion. *Energy Sources* 3:255–261.

———. 1978. Preliminary study of high neutron flux fusion heating. *Nuclear Engineering and Design* 49:212–215.

*Marcus, M. A.,* and *Lewis, A.* 1978. Resonance Raman spectroscopy of the retinylidene chromophore in bacteriorhodopsin ($bR_{570}$), $bR_{560}$, $M_{412}$ and other intermediates: structural conclusions based on kinetics, analogues, models and isotopically labeled membranes. *Biochemistry* 17:4722–4735.

*Matthews-Bellinger, J.,* and *Salpeter, M. M.* (1978). Distribution of acetylcholine receptors at frog neuromuscular junctions with a discussion of some physiological implications. *Journal of Physiology* 279:197–213.

*Mills, D.; Bilderback, D.;* and *Batterman, B. W.* 1978. Design and analysis of synchrotron radiation exit ports at Cornell High Energy Synchrotron Source (CHESS). In *Proceedings of 5th annual synchrotron radiation laboratory users' group meeting,* p. 100. Stanford, Calif.: Stanford Synchrotron Radiation Laboratory.

*Rackovsky, S.,* and *Lewis, A.* 1978. On the excited state energy surface of rhodopsin

and bacteriorhodopsin. In *Picosecond phenomena,* ed. C. V. Shank, E. Ippen, and S. L. Shapiro, pp. 330–335. Berlin: Springer Verlag.

*Rhodin, T. N.; Brucker, C. F.;* and Anderson, A. B. 1978. Analysis of acetylene and ethylene chemisorption and reaction on alpha-Fe(100) surfaces. *Journal of Physical Chemistry* 82:894.

*Salpeter, M. M.;* Rogers, A. W.; *Kasprzak, H.;* and *McHenry, F. A.* (1978). Acetylcholinesterase in the fast extraocular muscle of the mouse by light and electron microscope autoradiography. *Journal of Cell Biology* 78:274–285.

Shapiro, S. L.; Campillo, A. J.; *Lewis, A.; Perreault, G. J.; Spoonhower, J.; Clayton, R.;* and Stoeckenius, W. 1978. Picosecond and steady state, variable intensity and variable temperature emission spectroscopy of bacteriorhodopsin. *Biophysical Journal* 23: 384–393.

*Silcox, J.* 1978. Inelastic electron-matter interactions. In *Electron microscopy 1978. Proceedings of 9th international congress on electron microscopy,* vol. 3, ed. J. M. Sturgess, pp. 259–267. Toronto: Microscopical Society of Canada.

*Sulkes, M.; Lewis, A.;* and *Marcus, M.* 1978. Resonance Raman spectroscopy of squid and bovine visual pigments: the primary photochemistry in visual transduction. *Biochemistry* 17:4711–4722.

## ■ CHEMICAL ENGINEERING

*Evans, D. J.,* and *Streett, W. B.* 1978. Transport properties of homonuclear diatomics. II. Dense fluids. *Molecular Physics* 36:161–176.

*Gubbins, K. E.,* and *Twu, C. H.* 1978. Thermodynamics of polyatomic fluid mixtures. I. Theory. *Chemical Engineering Science* 33:863–878.

*Kubek, D. J.,* and *Shuler, M. L.* 1978. A rapid quantitative method to measure growth of plant cell suspension cultures. On the generality of methods to obtain single-cell plant suspension cultures. *Canadian Journal of Botany* 56:2340–2343; 2521–2527.

*Shuler, M. L.; Kargi, F.; Chang, J.; Slaby, J.;* and *Spatola, S.* 1978. Engineering and economic considerations in the conversion of animal manure to single cell protein. In *Proceedings of Cornell nutrition conference,* pp. 86–92. Ithaca, N. Y.: Cornell University.

*Smith, J. C.* 1978. Equipment for agitation blending and mixing. Chapter in *Review of American technology* (in Russian), ed. S. Schweers. Radnor, Pa., and Moscow: Chilton International (distributed in the USSR by the Soviet Ministry of Trade).

Steele, W. A., and *Streett, W. B.* 1978. Computer Simulations of Motion in Dense Fluids of Non-spherical Molecules. Paper read at Annual Meeting of American Chemical Society, 10–15 September 1978, in Miami Beach, Fla.

*Twu, C. H.,* and *Gubbins, K. E.* 1978. Thermodynamics of polyatomic fluid mixtures. II. Polar, quadrupolar and octopolar molecules. *Chemical Engineering Science* 33: 879–887.

*Webster, I. A.,* and *Shuler, M. L.* 1978. Mathematical models for hollow fiber enzyme reactors. *Biotechnology and Bioengineering* 20:1541–1556.

*Wiegandt, H. F.; Von Berg, R. L.;* and *Patel, P. R.* 1978. The cross flow piston bed. *Desalination* 25:303–324.

## ■ CIVIL AND ENVIRONMENTAL ENGINEERING

Alexander, K. D.; Mark, R.; and *Abel, J. F.* (1977). The structural behavior of medieval ribbed vaulting. *Journal of the Society of Architectural Historians* 36(4):241–251.

*Bisogni, J. J., Jr.,* and *Dick, R. I.* 1978. Discussion of "Activated sludge—unified design and operation" by T. M. Keinath, M. D. Ryckman, C. H. Dana, and D. A. Hofer. *ASCE, Journal of the Environmental Engineering Division* 104(EE5):1048–1050.

*Brutsaert, W.,* and *Chan, F. K.-F.* 1978. Similarity functions D for water vapor in the unstable atmospheric boundary layer. *Boundary-Layer Meteorology* 14(4):441–456.

*Brutsaert, W.,* and *Corapcioglu, M. Y.* (1978). Comparison of solutions for delayed-yield aquifers. *ASCE, Journal of the Hydraulics Division* 104(HY8):1188–1191.

*Dick, R. I.* 1978*a.* Discussion of "Underflow rate and control of an activated sludge process" by M. W. Schaffner and W. O. Pipes. *Journal of the Water Pollution Control Federation* 50:2604–2606.

———. 1978*b.* Factors Affecting Decisions Regarding Sludge Management. Paper read at Municipal Sludge Institute, 6–7 November 1978, at University of Wisconsin, Madison, Wis.

———. 1978*c.* Waste disposal—physical aspects. In *Proceedings of 20th annual public water supply engineers' conference,* pp. 87–97. Champaign-Urbana, Ill.: Engineering Publications Office, University of Illinois.

*Dick, R. I.;* Engelbrecht, R. S.; Nesbitt, J. B.; and Stephan, D. G. 1978. *Developments at 9th international conference on water pollution control.* Report of U.S. National Committee for Representation of the United States to the International Association on Water Pollution Research.

*Gergely, P.,* and *White, R. N.* 1978. Seismic effects in secondary containment vessels: research needs. *Nuclear Engineering and Design* 50:41–49.

Huffaker, C. B.; *Shoemaker, C. H.;* and Gutierrez, A. P. (1978). Current status, urgent needs and future prospects of integrated pest management. In *Strategies of pest control,* ed. D. Pimentel and E. H. Smith. New York: Academic Press.

*Kulhawy, F. H.,* and *Ingraffea, A. R.* 1978. Geomechanical model for settlement of long dams on discontinuous rock masses. In *Proceedings of international symposium on rock mechanics related to dam foundations,* vol. 1, pp. III.115–III.128. Rio de Janeiro: International Society for Rock Mechanics.

*Kulhawy, F. H.; Sangrey, D. A.;* and Clemence, S. P. 1978. Direct embedment anchors on sloping seafloors: state-of-the-art. Report to Naval Construction Battalion Center, Port Hueneme, Calif.

*Lawrence, A. W.; Bisogni, J. J., Jr.; Batchelor, B.;* and *Driscoll, C. T., Jr.* 1978. *Autotrophic denitrification using sulfur electron donors.* Report no. EPA–600/2–78–113, U.S. Environmental Protection Agency.

Liao, S. S. C., and *Sangrey, D. A.* 1978. Use of piles as isolation barriers. *ASCE, Journal of the Geotechnical Engineering Division* 104(GT9):1139–1152.

*Liu, P. L.-F.,* and Dalrymple, R. A. 1978. Waves over soft muds: a two-layer fluid model. *Journal of Physical Oceanography* 8(6):1121–1131.

*Loucks, D. P.*, and Chan, M.-L. 1978. Application of Stochastic Output Regulator Theory to Optimally Route Stormwater in a Sewer Network. Paper read at Chapman Conference on Kalman Filtering Theory and Techniques Applied to Water Resources, American Geophysical Union, 22–24 May 1978, in Pittsburgh, Pa.

*Lynn, W. R.* 1978. Environmental impact analysis and systems analysis in environmental quality. Regional Office for Southeast Asia: World Health Organization.

*O'Rourke, T. D.* 1978. *Tunneling for urban transportation: a review of European construction practice.* Urban Mass Transportation Administration, U.S. Department of Transportation report no. UMTA–II–06–0041–78–1.

*Stedinger, J.R.* 1978. Comment on "Value of Information in Reservoir Optimization" by V. Klemes. *Water Resources Research* 14 (5):984–986.

Stricker, H., and *Brutsaert, W.* 1978. Actual evapotranspiration over a summer period in the "Hupsel Catchment." *Journal of Hydrology* 39(½):139–157.

Weiler, W. A., Jr., and *Kulhawy, F. H.* 1978. *Behavior of stress cells in soil.* Niagara Mohawk Power Corporation, Syracuse, N.Y., report B–49(4).

*White, R. N.* 1978. Civil Engineering Curricula. Paper read at Annual Meeting of Northeast Region Civil Engineering Department Heads, 5–6 October 1978, at University of Massachusetts, Amherst, Mass.

## ■ COMPUTER SCIENCE

Akkoyunlu, E. A.; Bernstein, A. J.; *Schneider, F. B.;* and Silberschatz, A. 1978. Conditions for the equivalence of synchronous and asynchronous systems. *IEEE Transactions on Software Engineering* SE–4(6): 507–516.

## ■ ELECTRICAL ENGINEERING

*Costa, E.*, and *Kelley, M. C.* 1978*a*. Linear theory for the collisionless drift wave instability with wavelengths near the ion gyroradius. *Journal of Geophysical Research* 83:4365–4368.

———. 1978*b*. On the role of steepened structures and drift waves in equatorial spread F. *Journal of Geophysical Research* 83:4359–4364.

*Farley, D. T.* 1978*a*. Techniques for Correlation or Spectral Measurements of Scattered Radar Signals. Paper read at 19th General Assembly of the International Scientific Radio Union, 31 July–8 August 1978, in Helsinki, Finland.

———. 1978*b*. Turbulence in space: probing outdoor plasmas with radar. *Engineering: Cornell Quarterly* 13(2):8–14.

*Frey, J.* 1978. The merging of microwave and digital technologies. In *Proceedings of electronics and aerospace convention.* Washington, D.C.: Institute of Electrical & Electronics Engineers.

*Gonzales, C.; Kelley, M. C.;* Carpenter, L. A.; and Holzworth, R. H. 1978. Evidence for a magnetospheric effect on mid-latitude electric fields. *Journal of Geophysical Research* 83:4397–4399.

*Heetderks, W. J.* 1978. Principal component analysis of neural population response of knee joint proprioceptors in cat. *Brain Research* 156:51–65.

*Kelley, M. C.* 1978. The earth's electric field. *Engineering: Cornell Quarterly* 13(2):15–23.

*Kelley, M. C.*, and *Ott, E.* 1978. Two-dimensional turbulence in equatorial spread F. *Journal of Geophysical Research* 83:4369–4372.

*Kim, M.; Shin, K.;* and *Wheeler, B.* 1978. A system model of cell kinetics and its application to cancer chemotherapy. In *Proceedings of 1978 joint automatic control conference,* vol. 4, pp. 65–76. Pittsburgh, Pa.: Instrument Society of America.

*Kim, M.; Wheeler, B.;* and Perry, S. 1978. Quantitative description of cell cycle kinetics under chemotherapy utilizing flow cytometry. *Cell Tissue Kinetics* 11:497–512.

*Kratzer, S.*, and *Frey, J.* (1978). Transient velocity characteristics of electrons in GaAs with Γ-L-X conduction band ordering. *Journal of Applied Physics* 49:4064–4068.

*Levin, K.*, and *Tang, C. L.* 1978. Wavelength-modulation spectroscopy. *Applied Physics Letters* 33:817–819.

*Liboff, R. L.* 1978*a*. Hydroelectric solor energy conversion. *Energy Sources* 3:255–261.

———. 1978*b*. Preliminary study of high neutron flux fusion heating. *Nuclear Engineering and Design* 49:213–215.

Looft, F. J., and *Heetderks, W. J.* 1978. Real time correlator for detecting single units in peripheral nerve. *IEEE Transactions on Biomedical Engineering* 25:564–567.

*Ott, E.* 1978. Review of *Introduction to plasma physics* by B. M. Smirnov. *Physics Today* 31(9):51.

*Ott, E.;* Hui, B.; and Chu, K. R. 1978. Study of ECRH for Tokamaks. Paper read at Annual Meeting of Plasma Physics Division, American Physical Society, 30 October–3 November 1978, in Colorado Springs, Colo.

*Ott, E.*, and *Lovelace, R. V.* 1978. Lower Hybrid Scattering by Density Fluctuations. Paper read at Annual Meeting of Plasma Physics Division, American Physical Society, 30 October–3 November 1978, in Colorado Springs, Colo.

*Ott, E.*, and *Russell, D. A.* 1978. Diffuse boundary Rayleigh-Taylor instability. *Physical Review Letters* 41:1048–1051.

*Wersinger, J. M.; Ott, E.; Nation, J. A.;* and *Serlin, V.* 1978. Magnetic Shear Stabilization of the Diocotron Instability on a Relativistic Electron Beam. Paper read at Annual Meeting of Plasma Physics Division, American Physical Society, 30 October–3 November 1978, in Colorado Springs, Colo.

*Wolf, E. D.* 1978*a*. Limits in Lithography. Paper read at Meeting of New York State Section, American Physical Society, 13–14 October 1978, at IBM Watson Research Center, Yorktown Heights, N.Y.

———. 1978*b*. The national submicron facility. In *Proceedings of NSF workshop on opportunities for microstructures science, engineering and technology,* ed. *J. M. Ballantyne.* Ithaca, N.Y.: Cornell University.

## ■ GEOLOGICAL SCIENCES

*Brown, L.; Brewer, J.; Cook, F.; Long, G.;* and *Oliver, J.* 1978. COCORP Deep Seismic Reflection Studies of Continental Lithosphere: Regional Variations in Intrabasement Structure. Paper read at 48th Annual Meeting of Society of Exploration Geophysicists, 29 October–2 November 1978, in San Francisco, Calif.

*Brown, L. D.; Reilinger, R. E.;* Holdahl, S. R.; and Balazs, E. I. (1977). Post-seismic crustal uplift near Anchorage, Alaska. *Geophysics Research* 82:3369–3378.

*Cisne, J. L.* 1978. Trilobite Anatomy and its Bearing on Trilobite Relationships. Paper read at Meeting of Entomological Society of America, 26–30 November 1978, in Houston, Tex.

*Haxby, W. F.*, and *Turcotte, D. L.* 1978. On isostatic geoid anomalies. *Journal of Geophysical Research* 83:5473–5478.

*Kay, S. M.; Kay, R. W.; Hangas, J.;* and *Snedden, T.* 1978. Crustal xenoliths from potassic lavas, Leucite Hills, Wyoming (abstract). *Abstract Programs, Geological Society of America* 10:432.

*Ni, J.*, and *York, J.* 1978. Late Cenozoic tectonics of the Tibetan Plateau. *Journal of Geophysical Research* 83:5377–5384.

*Oliver, J.* 1978. Exploration of the continental basement by seismic reflection profiling. *Nature* 275:485–488.

*Ribando, R. J.; Torrance, K. E.;* and *Turcotte, D. L.* 1978. Numerical calculations of the convective cooling of an infinite sill. *Tectonophysics* 50:337–347.

*Smithson, S. B.* 1978. Modeling continent crust: structural and chemical restraints. *Geophysical Research Letters* 5:749–752.

*Smithson, S. B.; Brewer, J.; Kaufman, S.; Oliver, J.;* and Hurich, C. 1978*a*. Nature of the Wind River thrust, Wyoming, from COCORP data and from gravity data. *Geology* 6:648–652.

———. 1978*b*. Question of the Wind River thrust, Wyoming, resolved by COCORP deep reflection and by gravity data. In *30th annual field conference,* Wyoming Geological Association guidebook, pp. 227–234.

*Travers, W. B.* (1978). High pressure shales and oil spills on the U.S. Atlantic outer continental shelf (reply). *Science* 199:131–132.

———. 1978. Tectonics of the Intermontane Zone, British Columbia. Paper read at Penrose Conference, Geological Society of America, 15–20 October 1978, in Ascona, Switzerland.

*Turcotte, D. L.,* and Burke, K. 1978. Global sea-level change and the thermal structure of the earth. *Earth and Planetary Science Letters* 41:341–346.

## ■ MATERIALS SCIENCE AND ENGINEERING

*Blakely, J. M.* 1978*a*. Adsorption and Segregation: Metallurgy in Two Dimensions. Fairchild Lecture, 25 October 1978, at Lehigh University, Bethlehem, Pa.

———. 1978*b*. Adsorption, Segregation and Their Effect on Surface Structure. Paper read at Materials Research Conference, 29 November–1 December 1978, in Boston, Mass.

———. 1978*c*. Segregation to surfaces: dilute alloys of the transition metals. *CRC Critical Reviews of Solid State and Materials Sciences* 7:333–355.

*Eizenberg, M. E.,* and *Blakely, J. M.* 1978. Carbon Segregation to Stepped Ni Surfaces. Paper read at Meeting of American Vacuum Society, 27–30 November 1978, in San Francisco, Calif.

*Hadnagy, T. D.; Krenitsky, D. J.; Ast, D. G.;* and *Li, C.-Y.* (1978). Load relaxation studies of a metallic glass. *Scripta Metallurgica* 12:45–48.

*Koeller, R. C.,* and *Raj, R.* 1978. Diffusional relaxation of stress concentration at second phase particles. *Acta Metallurgica* 26:1551–1558.

## ■ MECHANICAL AND AEROSPACE ENGINEERING

*Caughey, D. A.* 1978. A systematic procedure for generating useful conformal mappings. *International Journal for Numerical Methods in Engineering* 12:1651–1657.

*Galskoy, A.,* and *Wang, K. K.* 1978. Melt temperature measurement in the mold during injection molding. In *Proceedings of technical conference, Injection Molding Division, Society of Plastics Engineers,* pp. I1–I14. Boston: Society of Plastics Engineers.

*Jahanmir, S.* 1978. Effect of Microstructure and Metallurgical Properties on the Wear of Metals. Paper read at TMS-AIME Fall Meeting, 15–19 October 1978, in St. Louis, Mo.

Levy, A. V., and *Jahanmir, S.* 1978. The Effects of the Microstructure of Ductile Alloys on Solid Particle Erosion Behavior. Paper read at TMS–AIME Fall Meeting, 15–19 October 1978, in St. Louis, Mo.

*Lumley, J. L.* 1978. Le Transport Turbulent: Comment Faire quand le Transport Gradient ne Marche Point. Paper read at Concertation sur les Methodes de Modelization d'Ecoulements Turbulents Complexes, ONERA/IMST Groupe de Travail, Institut de Mécanique Statistique de la Turbulence, 23–24 October 1978, at University of Aix-Marseille II, Marseille, France.

*Phoenix, S. L.* 1978. Series-Parallel Systems for Modelling the Failure of Fibrous Materials. Paper read at Joint National Meeting of ORSA-TIMS, 13–15 November 1978, in Los Angeles, Calif.

*Ribando, R. J.; Torrance, K. E.;* and *Turcotte, D. L.* 1978. Numerical calculations of the convective cooling of an infinite sill. *Tectonophysics* 50:337–347.

Wang, J. C. T., and *Shen, S. F.* 1978. Unsteady boundary layers with flow reversal and the associated heat-transfer problem. AIAA Journal 16(10):1025–1029.

*Wang, K. K.* 1978. New scientific methods for estimating cavity pressures and clamp forces in injection molding. In *Proceedings of technical conference, Injection Molding Division, Society of Plastics Engineers,* pp. N1–N17. Boston: Society of Plastics Engineers.

*Warhaft, Z.,* and *Lumley, J. L.* 1978. An experimental study of the decay of temperature fluctuations in grid-generated turbulence. *Journal of Fluid Mechanics* 88:659–684.

## ■ OPERATIONS RESEARCH AND INDUSTRIAL ENGINEERING

*Bechhofer, R. E.,* and *Turnbull, B. W.* (1978). Two (k + 1)–decision selection procedures for comparing k normal means with a specified standard. *Journal of the American Statistical Association* 73:385–392.

*Chow, F. I.;* Engel, P. A.; *Heath, D. C.;* and *Lawphongpanich, S.* 1978. Contact stress and wear study for type characters. *IBM Journal of Research and Development* 6:658–667.

*Cornuejols, G.,* and *Nemhauser, G. L.* (1978). Tight bounds for Christofides traveling salesman heuristic. *Mathematical Programming* 14:116–121.

*Engelbrecht-Wiggans, R.,* and *Maxwell, W.* Synchronization of discrete event simulations. *Management Science* 24:1417–1427.

Fisher, M. L.; *Nemhauser, G. L.;* and Wolsey, L. A. 1978. An analysis of approximations for maximizing submodular functions —II. *Mathematical Programming Study* 8: 73–87.

Garfinkel, R. S., and *Nemhauser, G. L.* 1978. *Programowanie calkowitzoliczbowe.* Polish translation of *Integer programming* (Wiley, 1972). Warsaw: Biblioteka Naukowa Inzynevin.

*Lucas, W. F.* (1978). *Report of the 4th international workshop on game theory* (held 18 June–1 July 1978, at Cornell University, Ithaca, N.Y.). Technical report no. 392, School of Operations Research and Industrial Engineering, Cornell University.

———. 1978. *The apportionment problem.* Technical report no. 388, School of Operations Research and Industrial Engineering, Cornell University.

*Merchant, D. K.,* and *Nemhauser, G. L.* (1978). A model and algorithm for the dynamic traffic assignment problem. Optimality conditions for a dynamic traffic assignment model. *Transportation Science* 12:183–199; 200–207.

*Nemhauser, G. L.,* and Wolsey, L. A. (1978). Best algorithms for approximating the maximum of a submodular set function. *Mathematics of Operations Research* 3:177–188.

*Nemhauser, G. L.;* Wolsey, L. A.; and Fisher, M. L. (1978). An analysis of approximations for maximizing submodular functions—I. *Mathematical Programming* 14:265–294.

*Schruben, L. W.* 1978. Correlation Hypotheses in Simulation Experiments. Using a Random Confidence Coefficient to Compare Interval Estimators. Invited papers read at Joint National Meeting of ORSA–TIMS, 13–15 November 1978, in Los Angeles, Calif.

*Turnbull, B. W.*, and *Weiss, L.* 1978. A likelihood ratio statistic for testing goodness of fit with randomly censored data. *Biometrics* 34:367–375.

*Weiss, L.* (1978). The error in the normal approximation to the multinomial with an increasing number of classes. *Naval Research Logistics Quarterly* 25:257–261.

————. 1978. Some tests of whether several samples are from identical populations. *Communications in Statistics A* 12:1099–1127.

## ■ PLASMA STUDIES

*Dreike, P. L.; Hammer, D. A.; Sudan, R. N.;* and *Wiley, L. G.* 1978. Generation and propagation of an intense rotating proton beam. *Physical Review Letters* 41(19):1328–1331.

*Finn, J. M.*, and *Sudan, R. N.* 1978. Resonant effects on the low-frequency Vlasov stability of axisymmetric field-reversed configurations. *Physical Review Letters* 41(10): 695–698.

*Sudan, R. N.* (1978). Ion-ring ignitor for inertial fusion. *Physical Review Letters* 41 (7):476–480.

Tsakiris, G. D.; Boyd, D. A.; *Hammer, D. A.;* Trivelpiece, A. W.; and Davidson, R. C. 1978. Electron energy distribution of a mirror confined relativistic plasma inferred from synchrotron radiation. *Physics of Fluids* 21 (11):2050–2062.

## ■ THEORETICAL AND APPLIED MECHANICS

*Burns, J. A.* 1978. On the dynamical evolution and origin of the Martian moons. *Vistas in Astronomy* 22:193–210.

*Burns, J. A.*, and Harris, A. W. 1978. Asteroid Rotation Rates and Shapes. Paper read at Meeting of Planetary Sciences Division, American Astronomical Society, 30 October–3 November 1978, in Pasadena, Calif.

*Cole, E. H., Jr.*, and *Conway, H. D.* 1978. Analysis of structural members under point loadings. *International Journal of Mechanical Sciences* 20(9):571–579.

Cuzzi, J. N.; *Burns, J. A.;* Durisen, R. H.; and Hamill, P. 1978. Vertical Structure and Thickness of Saturn's Rings. Paper read at Meeting of Planetary Sciences Division, American Astronomical Society, 30 October–3 November 1978, in Pasadena, Calif.

*Goguen, J.*, and *Burns, J. A.* 1978. Escape from the Martian Satellites! Paper read at Meeting of Planetary Sciences Division, American Astronomical Society, 30 October–3 November 1978, in Pasadena, Calif.

*Holmes, P. J.* 1978*a*. Averaging, Global Motions and Chaos in Forced Oscillations. Strange Nonlinear Oscillations. Invited papers read at Mathematics Department Colloquium, Memorial University of Newfoundland, 12 October 1978, in St. Johns, Canada.

————. 1978*b*. Pipes supported at both ends cannot flutter. *Journal of Applied Mechanics* 45:619–622.

*Kilgore, T. R.; Burns, J. A.;* and Pollack, J. B. 1978. Orbital Evolution of "Phobos" Following its "Capture". Paper read at Meeting of Planetary Sciences Division, American Astronomical Society, 30 October–3 November 1978, in Pasadena, Calif.

Marsden, J. E., and *Holmes, P. J.* 1978. Bifurcations of dynamical systems and nonlinear oscillations in engineering systems. In *Nonlinear partial differential equations and applications*, ed. J. M. Chadam. Proceedings of a seminar held at Indiana University, 1976–77. Springer Lecture Notes in Mathematics no. 648. Berlin: Springer Verlag.

*Rand, R. H.* 1978. The dynamics of an evaporating meniscus. *Acta Mechanica* 29:135–146.

*Rand, R. H.*, and *Cooke, J. R.* 1978. Fluid dynamics of phloem flow. *Transactions of the ASAE* 21:898–900.

## ■ GENERAL

*Gardner, R. E.* 1978*a*. Contracting for Advising Services. Orienting Students to Faculty Advising Systems. Papers read at 2nd National Conference on Academic Advising, 19 October 1978, in Memphis, Tenn.

————. 1978*b*. Managing faculty advising. In *Academic advising*, ed. D. Crockett. Iowa City, Iowa: American College Testing Service. (Reprints available from the Division of Basic Studies, Cornell College of Engineering.)

*Simmons, R.* 1978*a*. Funding Special Programs. Paper read at Annual Conference for Directors of Special Minority Engineering Programs, Committee on Minorities in Engineering, National Research Council, 3 November 1978, in Washington, D.C.

————. 1978*b*. Survey on Teaching in Engineering—a Summary Report. Paper read at Annual Conference of the American Society of Mechanical Engineers, December 1978, in San Francisco, Calif.

————. 1978*c*. Teaching and Learning in Special Engineering Programs. Paper read at Annual Conference of Society of Ethnic and Special Studies, 26 October 1978, in Houston, Tex.

ENGINEERING
Cornell Quarterly

Published by the College of Engineering, Cornell University

*Editor:* Gladys McConkey

*Associate Editor:* Terrence Holt

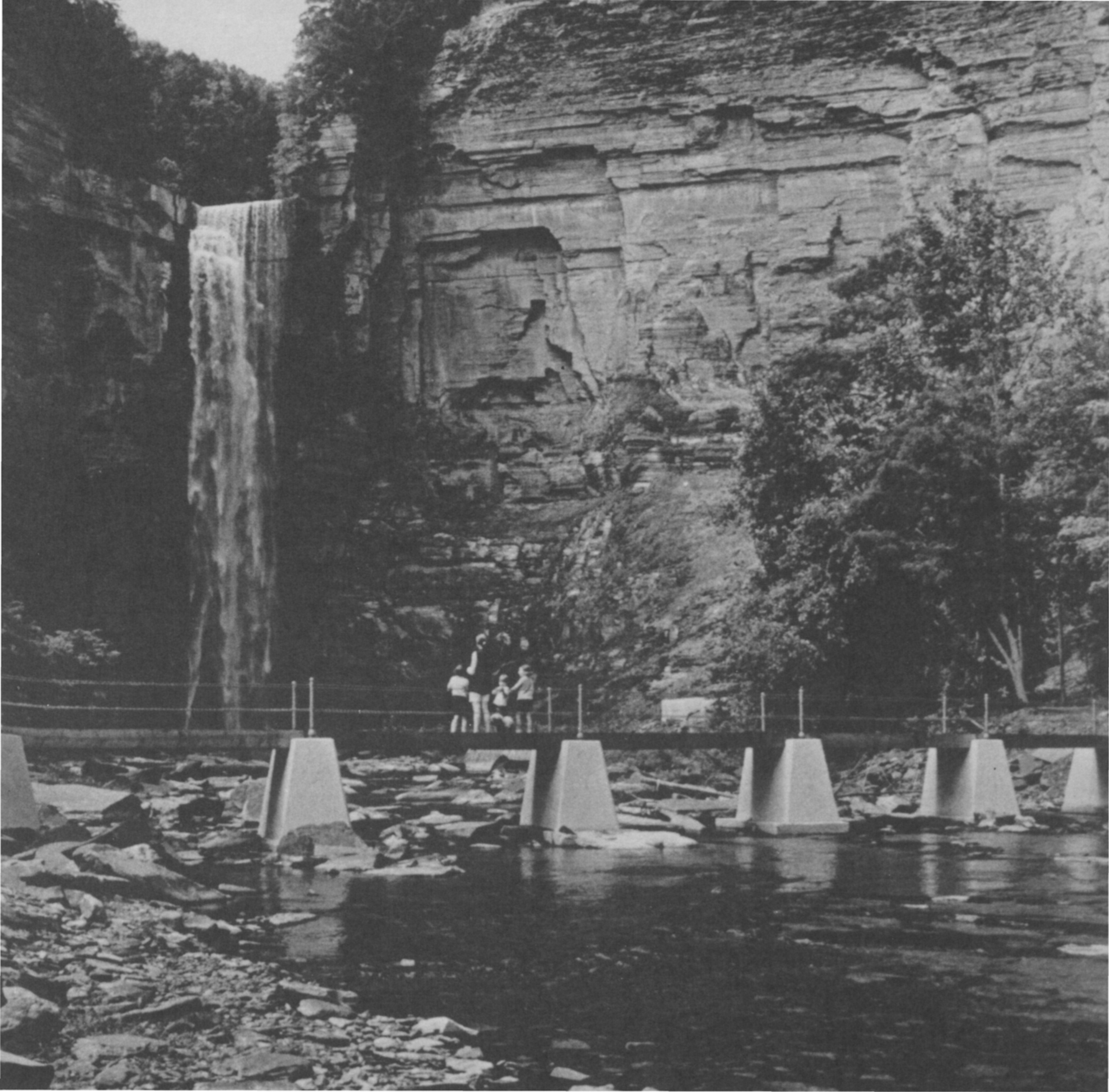
*Graphic Art Work:* Francis Russell

*Lithographers:* General Offset Printing Co., Springfield, Massachusetts

*Typography:* Eastern Typesetting, So. Windsor, Connecticut 06074

*Photographic credits for this issue are as follows:*
*R. G. Bea: 14, 16, 17, 18(1), 19, inside front cover*
*Yong Kim: 34*
*Burt Levenhagen: 9*
*Ta Liang: 4(3)*
*Jon Reis: 1(from top: 2, 3, 5, 7), 8(bottom), 12, 18(3) 20, 26, 30, 33(1,3), 39(center), 43*
*David Ruether: 36, 40, 41, 42*
*C. Hadley Smith: 33(2)*

Please address any correspondence, including notification of change of address, to ENGINEERING: Cornell Quarterly, Carpenter Hall, Ithaca, New York 14853.



**ENGINEERING**
Cornell Quarterly
ISSN 0013-7871
Carpenter Hall, Ithaca, N. Y. 14853

*Return postage guaranteed*

Second Class
Postage Paid at
Ithaca, N. Y. 14850