ENGINEERING

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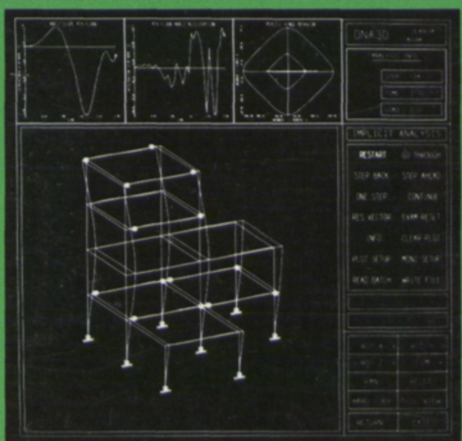

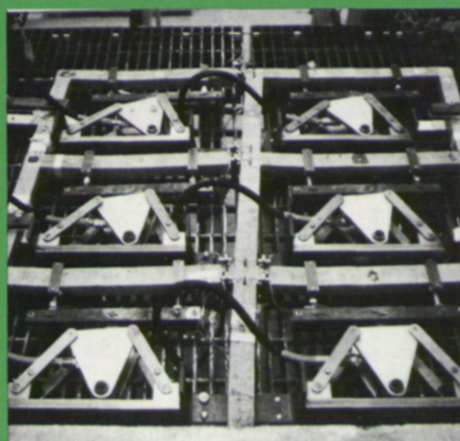

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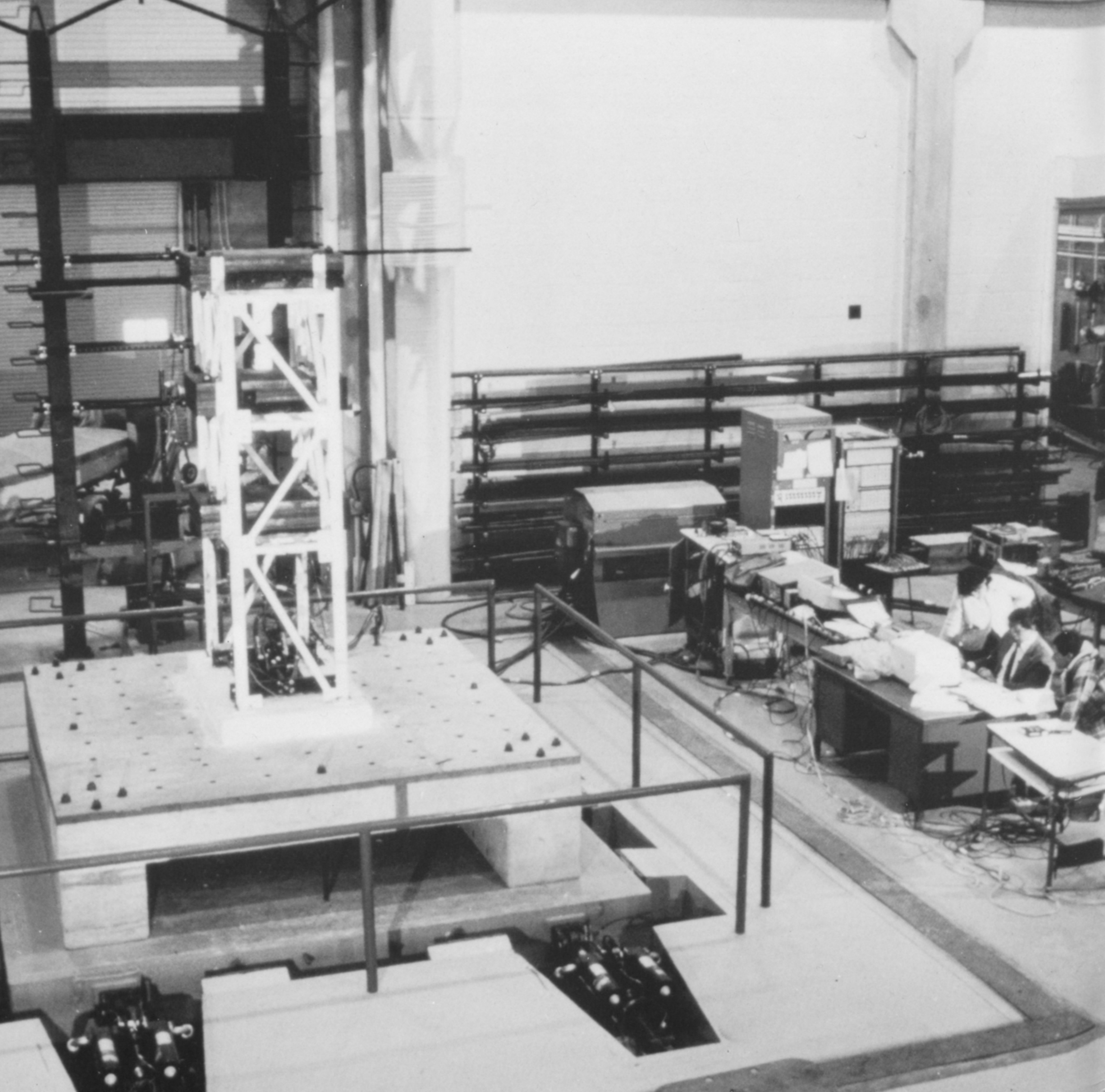
RESEARCH IN EARTHQUAKE ENGINEERING



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Opposite: Earthquake motions can be simulated for experimental testing by using shaking tables such as this one at the State University of New York at Buffalo. This table, one of the most sophisticated in the world, is used for a number of projects that are part of the program of the new National Center for Earthquake Engineering Research.

Cover illustrations: Damage from a 1980 earthquake in Algeria; a computer simulation, part of a Cornell research project in nonlinear dynamic analysis of a building; structural models tested in a Cornell laboratory for response to simulated seismic action.

THE NEW NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

by Peter Gergely

The choice of New York State as the location of the first national earthquake engineering research center surprised many people. The commonly held view is that damaging earthquakes do not occur east of the Rocky Mountains and therefore can be ignored. Actually, however, major seismic disturbances do occur in the East. In fact, the highest-magnitude earthquakes in the United States in recorded history were centered in Missouri.

Cornell, which has been active in earthquake research for many years, is one of several universities in New York State that are part of the new center. The headquarters are at the State University of New York at Buffalo, and SUNY/Buffalo's Robert L. Ketter is serving as director. The National Science Foundation has allocated $5 million a year for five years, provided that matching funds are secured. Thus the total potential funding is $50 million for the five-year period.

CHANGING THE PERCEPTIONS OF SEISMIC HAZARD

Earthquakes in the East have been both intense and widespread. Those highest-magnitude quakes centered at New Madrid, Missouri, were part of a series that occurred over a four-month period in 1811 and 1812; the three largest had estimated magnitudes of 8.4, 8.6, and 8.7, and were felt all the way up the coast, stopping clocks in Washington, shaking buildings in New York, and ringing bells in Boston. Another large earthquake, in 1886, was centered in Charleston, South Carolina; that one was felt as far away as Chicago.

Over the past two and one-half centuries, major earthquakes have occurred in three regions at moderate distances from Cornell's location in Ithaca, New York. These regions are along the St. Lawrence River valley, in the Attica-Niagara area, and in eastern New England. For example, in 1732 an earthquake of magnitude 7.0 occurred near Montreal. The town of Charlevoix, near the mouth of the St. Lawrence, experienced quakes of magnitude 6.0, 6.5, and 7.0 in 1860, 1870, and 1925. In 1944 a quake of magnitude 6.0 was registered in Massena, New York. And in Newfoundland a quake of magnitude 7.0 broke twelve transatlantic cables and created seismic sea waves that caused loss of life.

Why, then, is earthquake hazard in the East so little recognized? One reason is that most Eastern faults are deep in the Earth's crust, without visible features such as those along California's San

EARTHQUAKE MAGNITUDE AND INTENSITY

The commonly used Richter scale of magnitude expresses the amount of energy release in an earthquake; a magnitude of 5 or more is considered large. Because the scale is logarithmic, an increase of 1 in the magnitude corresponds to a tenfold increase in the amplitude of motion near the epicenter, and approximately a 32-fold increase in energy release.

Intensity, expressed in Roman numerals, is an indication of the amount of damage or shaking that occurs at given distances from the earthquake epicenter. An intensity of VII or higher in the region surrounding the epicenter is characteristic of a major disturbance.

Figure 1

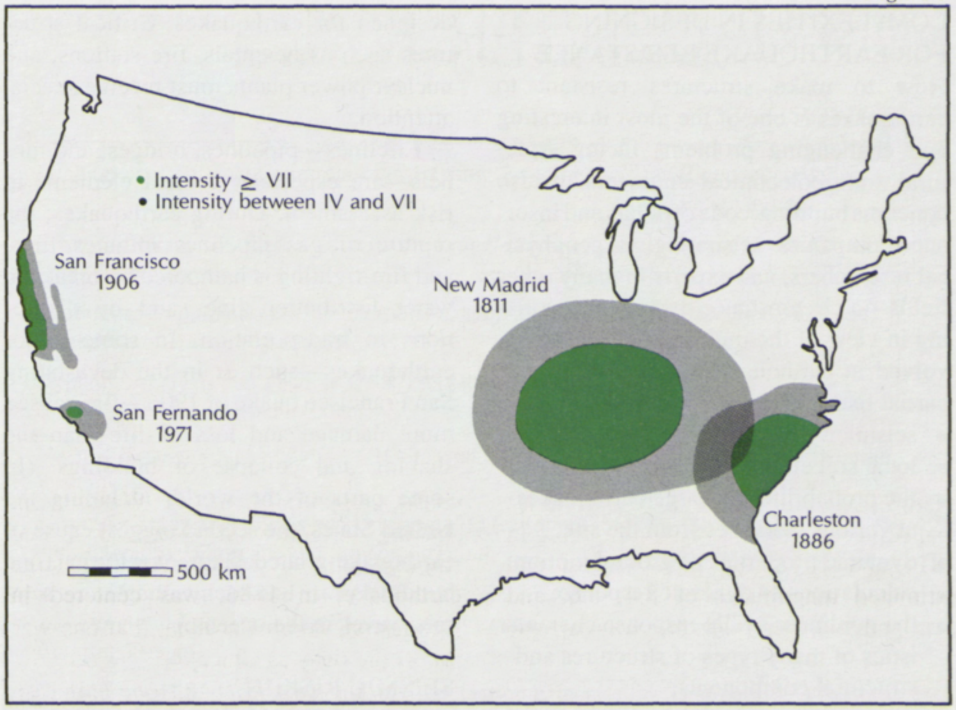


Figure 1. Earthquakes in the East and Midwest affect much larger geographic areas than earthquakes of comparable magnitudes in California. The intensities of four major earthquakes are indicated on the map.

A very widespread quake centered near Lawrenceville, Illinois, occurred on June 10, while this magazine was in production. The quake, of magnitude 5.0, was felt in sixteen states and parts of Canada. Shaking that lasted from 10 seconds to almost a minute disrupted telephone service in three counties and caused minor damage such as broken windows over a wide area. People were evacuated from a swaying twelve-story apartment building in Columbia, South Carolina, seven hundred miles from the quake center.

Andreas Fault. Also, people's memories are short. In the eastern part of the country, about twenty-five years elapse between major earthquakes, and catastrophic quakes occur on the average of once in at least five hundred years, as compared with California's rate of about one per century.

When large earthquakes do occur in the East, however, the risk to life and property is greater. For one thing, seismic waves travel much farther in the East than in the West; the affected region is larger by a factor of ten to twenty, as evidenced by the New Madrid and Charleston quakes (see Figure 1). Also, the large affected area would include many densely populated areas; a repeat of the 1811–12 events would be devastating. An additional factor is that in the East the vast majority of structures, including buildings, bridges, and pipelines, were not designed to resist earthquake forces. The matter is urgent, for some experts predict that a quake of magnitude 6 will occur in the eastern United States in the next few years.

Investigators in the group of universities that make up the new National Center for Earthquake Engineering Research (NCEER) will focus their attention, at least initially, on the Northeast. They intend to study earthquakes from an engineering point of view, assessing the hazards and making recommendations for design criteria. The main research areas are ground motion; soil dynamics and soil-structure interaction; system response and unserviceability; laboratory and field experiments; innovative computing and expert systems; issues related to codified design; and societal and educational issues.

Meaningful reduction in earthquake hazard will require the solution of many difficult and diverse problems, but although the task is complex, the technical aspects are fascinating and challenging.

In recent years, government funding for the research has increased somewhat. The United States Congress passed the National Earthquake Hazard Reduction Program (NEHRP) in 1977. The primary source of funding for research at universities and other institutions has been the National Science Foundation.

Other countries that have active research programs include Japan, New Zealand, Italy, Canada, Mexico, Taiwan, the People's Republic of China, and Yugoslavia. Frequent national and international conferences in earthquake engineering attract many participants, and international cooperative research is growing.

“...the greatest hazard is presented not by new structures, including tall buildings, but by old buildings.”

COMPLEXITIES IN DESIGNING FOR EARTHQUAKE RESISTANCE

How to make structures resistant to earthquakes is one of the most interesting and challenging problems facing structural and geotechnical engineers. It also concerns building-code officials and insurance companies, seismologists, geophysical researchers, and experts in many other fields—a circumstance that is not surprising in view of the multitude of factors involved in earthquake-resistant design. A partial listing of these factors is:

- seismicity of a region;
- local soil effects;
- the probabilities of large earthquakes at various distances from the site;
- dynamic properties of ground motion;
- calculations of dynamic response;
- the nonlinear cyclic response characteristics of many types of structures and structural components;
- costs entailed in building structures for earthquake resistance;
- probabilistic risk assessment of various kinds of structures;
- properties of structures already built;
- the formulation of design goals for preventing loss of life, or for preventing or limiting structural damage;
- problems associated with local soil failures, fires, and pipeline ruptures.

Because of uncertainties about such factors as ground motion and the response of structure-soil systems, the assessment of risk must be explicitly or implicitly probabilistic. The risk analysis is especially difficult in regions, such as the eastern United States, where large earthquakes are possible but infrequent.

Another difficulty is that the greatest hazard is presented not by new structures, including tall buildings, but by old buildings; in the East these have rarely been designed for earthquakes. Critical structures such as hospitals, fire stations, and nuclear power plants must receive special attention.

Lifelines—pipelines, bridges, and tunnels—are especially critical elements in risk assessment. During earthquakes, the rupture of gas pipelines initiates fires, and fire-fighting is hampered by breaks in water-distribution lines and by disruptions in transportation. In some major earthquakes—such as in the devastating San Francisco quake of 1906—fire caused more damage and loss of life than the shaking and collapse of buildings. (In some parts of the world, including the United States, the second biggest cause of earthquake-related deaths over the past one hundred years has been tsunamis, or seismic waves in the oceans.)

SEISMIC RISK IN THE EASTERN UNITED STATES

Assessing the risk in the East is difficult: good statistical models cannot be developed because major earthquakes occur so infrequently. Instrumental data, in particular, are very scarce.

As a consequence, a major question facing engineers, property owners, public officials, and insurance companies in the East is whether it is necessary to design structures to resist earthquakes and to what extent. Should structures be designed just to avoid collapse in the event of a large earthquake? Or should the aim also be to limit damage in moderate earthquakes? And what about existing buildings—should they be strengthened, and if so, how?

Most experts are of the opinion that, as a minimum, critical structures must be designed or reinforced so that they would remain operational even in a major earth-

FIRST-YEAR PROJECTS AT CORNELL

Topic	*Principal Investigators*
Evaluation of Seismic Performance of Existing Buildings	Richard N. White, Peter Gergely
Effects of Grain Size Distribution on the Liquefaction Potential of Gravels and Silts	Harry E. Stewart
Estimating Building Stocks for Earthquake Mitigation and Protection of Historic Structures	Barclay G. Jones
Dynamic Analysis and Testing of Structures and Structural Components under Seismic Loads	Richard N. White, Peter Gergely
Seismic Response and Reliability Analysis of Lifeline Systems	Thomas D. O'Rourke, Mircea Grigoriu
Seismic Nonlinear Analysis and Design of 3D Buildings with Interactive Graphics and Supercomputing	John F. Abel, William McGuire
Knowledge-Based System for Preliminary Architectural and Structural Engineering in Earthquake-Resistant Building Design	Peter Gergely, John F. Abel
Cooperative U.S.–Japan Research on Liquefaction Effects on Buried Pipelines	Thomas D. O'Rourke
Workshop on Computers in Earthquake Engineering	William McGuire, John F. Abel
Workshop on Expert Systems in Earthquake-Resistant Design	Peter Gergely

quake. These structures include hospitals, fire stations, major bridges, gas and water pipelines, and, of course, power plants. The Northeast is deficient in this regard and much work needs to be done, not only to assess the many technical problems, but also to increase awareness among code officials, the engineering community, and the public.

RESEARCH PLANS AT THE NEW CENTER

The annual funding for the National Center for Earthquake Engineering Research is $10 million if federal funds are matched, or more if non-federal funds exceed the amount from NSF. For the first year, the matching $5 million was obtained from New York State, and additional contributions came from industrial sources and from the participating research institutions.

The major participants, in addition to Cornell and SUNY/Buffalo, are Columbia University and Columbia's Lamont-Doherty Geological Observatory. Other institutions that are involved include the City College of New York, Lehigh University, Princeton University, and Rensselaer Polytechnic Institute. In addition, researchers from dozens of universities and design offices will participate in cooperative research programs. Experts in such diverse areas as structural dynamics, artificial intelligence, seismotectonics, and information science are being brought together by the center.

The management structure was, in fact, a key aspect of the group's proposal to NSF. Another feature was that the programs outlined were oriented toward specific goals and had a strong technology-transfer component. The prospects for continued matching funds for at least five years were shown to be promising.

The combined resources of the participating institutions provide a superior facility. SUNY/Buffalo, for instance, has a medium-sized modern shaking table (12 by 12 feet) with five degrees of freedom. Cornell, as one of the core experimental facilities, will upgrade the equipment here for research in structural dynamics and soil dynamics. With a $500,000 allocation to the university for the first year, we will acquire modern dynamic loading equipment and install or modernize data-acquisition devices. The overall facilities also include large- and small-scale simulators and materials-testing equipment, measuring devices, supercomputer and computer-graphics systems, and a wide range of digital and analog support systems.

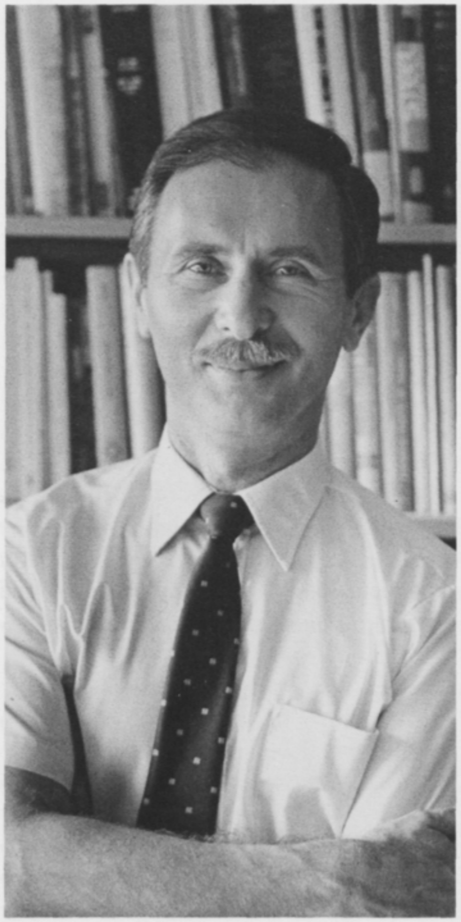
CORNELL'S PART IN THE PROGRAM

The Department of Structural Engineering at Cornell is a major participant in the center. A number of our members contributed to the writing of the proposal; I am one of the five co-principal investigators and a member of the executive committee; and seven of our faculty members are taking part in the research this first year.

The Cornell projects now underway are listed in the table on the preceding page. Heading them are John F. Abel, Peter Gergely, Mircea Grigoriu, William McGuire, Thomas D. O'Rourke, Harry E. Stewart, and Richard N. White of the structural engineering department, and Barclay G. Jones of the Department of City and Regional Planning. The expertise of this group covers a wide range of topics, from structural and geotechnical engineering to societal and economic issues. In the future we may be joined by others in the College of Engineering who are conducting earthquake research in other departments —people in the geological sciences and in theoretical and applied mechanics.

To cope with the large volume of work, on top of an already active research program, the center at Cornell will hire about a dozen people, including two or three postdoctoral researchers, six to eight graduate research assistants, and support staff. Christopher H. Conley, who is joining us as a senior research associate, will serve as a manager in addition to participating in two or three projects.

The research undertaken by the National Center for Earthquake Engineering Research is important and interesting, presenting large challenges and opportunities, and we are excited about participating in the activities.



Peter Gergely is director of the School of Civil and Environmental Engineering at Cornell and chairman of the school's Department of Structural Engineering, and he is now heading the Cornell program that is part of the new National Center for Earthquake Engineering Research.

A specialist in structural mechanics and dynamics, his research interests include reinforced concrete and shell structures, as well as earthquake engineering.

Gergely received his undergraduate education at the Technical University of Budapest and at McGill University in Montreal. He worked as a draftsman and structural engineer before and after graduation from McGill, and joined the Cornell faculty after completing doctoral study at the University of Illinois in 1963. He has spent sabbatical leaves at the Pittsburgh–Des Moines Steel Company (1969), the Hungarian Academy of Sciences and the University of Toronto (1976), and the Lawrence Livermore National Laboratory and the University of California at Berkeley (1983).

He is a fellow of the American Society of Civil Engineers (ASCE) and is a fellow and director of the American Concrete Institute (ACI). He has received four national awards, including the ACI's 1982 Distinguished Service Award.

SAFEGUARDING THE LIFELINES

by Thomas D. O'Rourke and Mircea D. Grigoriu

Our way of life depends on pipelines, cables, and transportation facilities. Damage to any of these systems can cause injuries, threaten public sanitation and health, and affect the economy of an entire region.

A principal cause of such damage is earthquakes. After the 1985 Chilean earthquake, for example, aqueduct failures disrupted the water supplies to Valparaiso, Viña del Mar, and San Antonio. The 1985 Guerrero-Michoacán quake caused more than 7,200 breaks and serious leaks in water transmission and distribution pipelines in Mexico City, leaving some 4.5 million people without water.

One of the worst pipeline failures in history occurred in March of this year in Ecuador. More than sixteen miles of the trans-Ecuadorian pipeline sustained damage from massive ground failures accompanying a major earthquake. Since the pipeline moved virtually all of Ecuador's export oil, the failure has deprived the country of 60 percent of its export revenue—an estimated $5 million a day.

Even moderate earthquakes have caused extensive damage to water, sewer, gas, and electricity systems. In the 1971 quake in San Fernando, California, for example, more than 1,400 water and sewage pipeline breaks resulted in nearly complete loss of water in the city, and disruption of service to about 27,000 gas and 250,000 electricity customers.

Prompted by the difficulties in San Fernando, the engineering community in the United States, with assistance from the National Science Foundation, developed a program to evaluate and reduce seismic damage in complex service systems. This program has grown with international participation to become a distinct field, known as *lifeline earthquake engineering*.

THE LIFELINES AND THEIR VULNERABILITY

The Technical Council on Lifeline Earthquake Engineering has identified four major types of lifelines: electric power and telecommunications; gas and liquid fuel; transportation; and water and sewage. A survey of the facilities associated with these systems (see the table on the following page) shows that they encompass a wide range of services with many complex features.

Because lifelines cover large areas, they are subject to variations in earthquake intensity. Seismic energy attenuates with distance and the amount of seismic disturbance is affected by differences in soil, rock, and groundwater conditions. In addition to variations in geotechnical site characteristics throughout a region, there are often substantial differences in the mechanical and structural characteristics of components in a single lifeline system. Because of these variations, and because lifelines serve multiple functions, it is necessary to have methods of analysis and planning that optimize the overall performance. In other words, a systems engineering approach is needed.

Lifelines are *interconnected;* they are parts of networks that involve different pathways, components of variable strength, and valving and switching mechanisms. Furthermore, lifelines are *interdependent;* damage in one system can affect the performance of another. For example, the rupture of gas or liquid fuel lines may be a source of fire, a contingency that must be considered in the post-earthquake use of water distribution networks. Other examples of interdependence are simultaneous breakage of water and sewage lines, which creates a health hazard; and loss of electric power to pumping stations, which limits the supply of water and places greater emphasis on the transportation network for emergency repairs and water distribution.

The systems performance of interconnected and interdependent lifelines is a principal focus of Cornell research in lifeline earthquake engineering. Another aspect is the study of geotechnical conditions that influence earthquake hazards.

CORNELL RESEARCH ON GEOTECHNICAL HAZARDS

Among the principal geotechnical hazards associated with earthquakes are permanent ground movements, including active faulting, soil liquefaction, landslides, and vibration-induced soil settlement.

Soil liquefaction, which is discussed in this issue in the article by Harry E. Stewart, is the transformation of saturated soil from a solid to a liquid phase as a result of increased pore water pressure and loss of shear strength. Under the appropriate conditions, massive flow failures can occur. For example, 98 million cubic yards of sediment at Valdez liquefied during the 1964 Alaska earthquake, destroying the port. The town had to be relocated in a more stable area.

Illustrations of pipeline deformation caused by permanent ground movements are shown in Figures 1 and 2.

In research conducted by our group at Cornell, we have catalogued permanent deformations that occurred during historic earthquakes and have summarized the effects of ground movement on buried pipelines. In addition, we have performed full-scale experiments to quantify the characteristics of interaction between soil and buried piping. These findings on soil-structure interaction have been incorporated in guidelines issued by the American Society of Civil Engineers, and in design methods used by several utility companies.

We have also developed a sophisticated computer program, UNIPIP, that can model complex patterns of soil displacement, elasto-plastic soil response, and the performance of pipeline materials well beyond yield stress. This capability is important because the one-time, extreme nature of earthquake-induced loading makes it economically infeasible to design buried pipelines for stresses that might be experienced in the event of ground failure. Instead, the design can take advantage of pipeline ductility. With the capabilities of the computer program, engineers can evaluate the behavior of high-pressure pipelines, even under the

LIFELINES AND THEIR COMPONENTS

Based on categories used by the Technical Council on Lifeline Earthquake Engineering (1983)

Type of System	*Line Components*	*Support Facilities*	*Terminal Facilities*
Electric Power and Telecommunications	Overhead lines, buried cables, offshore cables, and tunnels	Electric substations, telephone equipment buildings, radio transmission towers, and computers	Power plants, including fossil-fuel, nuclear, and hydroelectric developments
Gas and Liquid Fuel	Subsurface and elevated pipelines, including continuous welded, jointed, and bolted pipelines	Pumping stations, regulator stations, storage tanks, and underground storage facilities	Oil and gas fields, and port facilities
Transportation	Highways, secondary roads, railroads, rapid-transit lines bridges, and tunnels	Railroad and rapid-transit stations, retaining structures, and embankments	Harbors and airports
Water and Sewage	Subsurface and elevated pipelines, including continuous welded, jointed, and bolted pipelines; irrigation culverts, aqueducts, and tunnels	Storage tanks, wells, and pumping plants	Reservoirs, earth and concrete dams, and wastewater-treatment works

"...lifelines are interdependent; damage in one system can affect the performance of another."

Figure 1

Figure 2

Figure 1. Pipelines were ruptured and deformed near the San Fernando fault after the 1971 earthquake. Surface faulting contributed to the pipeline damage. Sewage (upper) and water (middle) pipelines have pulled apart at the joints; the continuous, welded gas pipeline (lower) has buckled. (Photo courtesy of the Southern California Gas Company)

Figure 2. Beam buckling of a pipeline at a site in Taft, California, on the Buena Vista Hills fault. Charles Trautmann, a Cornell research associate, is inspecting a 16-inch-diameter oil-gathering pipeline that has buckled out of the ground because of compressive forces from ground movement.

This was an inactive reverse fault that was activated by the removal of subsurface fluids. Cornell researchers investigated the site to gain a better idea of pipeline deformation from ground failure typical of actual earthquakes. (Photo by T. D. O'Rourke)

Cornell Team Surveys Damage from the March 1987 Earthquakes in Ecuador

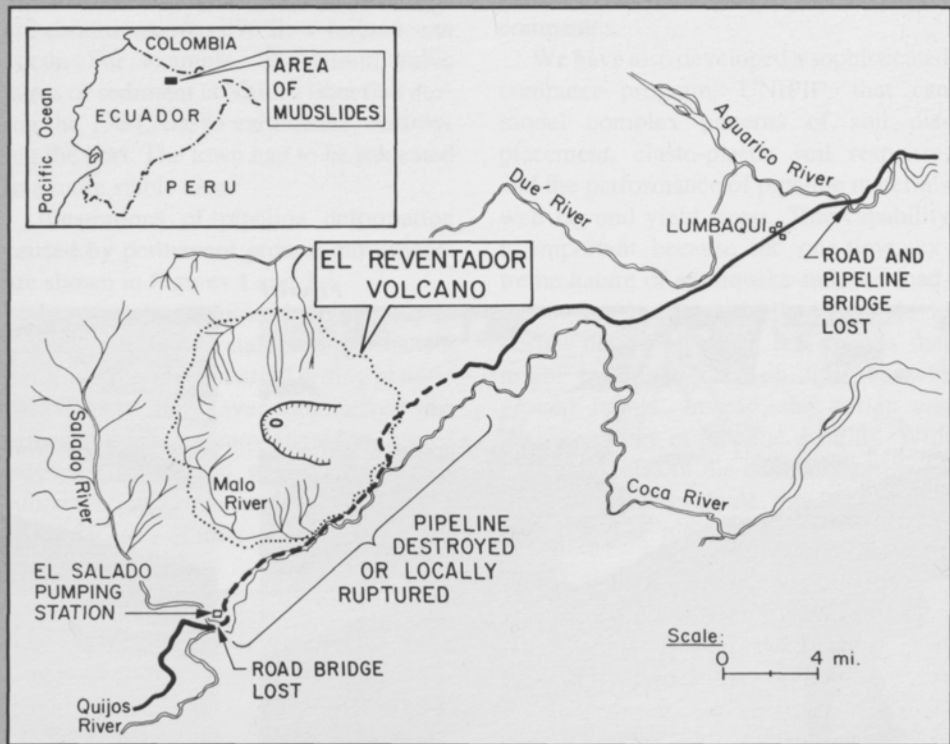
An earthquake reconnaissance team of Cornell researchers made a comprehensive engineering assessment of damage from two disastrous earthquakes on March 5 in Ecuador that killed an estimated one to two thousand people. A major catastrophe was the damage to a crude-oil pipeline: virtually all oil exports have been cut off, depriving the country of 60 percent of its export revenue—an estimated $5 million a day.

The Cornell team was organized by Professor Thomas D. O'Rourke immediately after the earthquakes were recorded. Team members Esteban Crespo (who is from Ecuador) and Kenneth J. Nyman, doctoral candidates in civil and environmental engineering, were at the site by March 19 (they had to wait for Nyman to get the necessary shots). A briefing was given by the three-man team to the National Research Council's Committee on Natural Disasters on April 17.

The mission was sponsored by the National Center for Earthquake Engineering Research and by the Technical Committee on Lifeline Earthquake Engineering of the American Society of Civil Engineers.

According to the team report, the pipeline damage was caused by massive ground failures, not by earthquake shaking. Debris slides and river flooding, rather than dynamic loads on the pipe, were largely responsible. All the breaks occurred in above-ground portions of the pipeline, the researchers found; less damage would have resulted if the line in certain regions had been buried the standard three feet below ground. The 260-mile-long line runs from oil fields east of the Andes to the port of Esmeraldas on the Pacific Ocean, and only the western part, in the more inhabited areas, was built underground. The 26-inch pipeline transported 250,000 barrels of oil a day.

1



2

1. The map shows locations of damage.
2. This section of oil pipeline was severed by landslide and river scour. A narrow oil slick within the river, at upper left, indicates the previous location of lost pipe. An undamaged pipeline segment is visible to the right.

3

4

The earthquakes, of magnitude 6.1 and 6.9, occurred in the northeastern part of the country, near the active volcano El Reventador. The area around the epicenters had received 24 inches of rain in the previous month and strong ground-shaking triggered debris slides and avalanches of loosened rock. The Cornell engineers, who surveyed the area by helicopter and truck, estimated that over 100 million cubic yards of soil and rock had been displaced. Flooding caused by the influx of landslide material was responsible for most of the loss of life. "Some villagers were simply buried without a trace," O'Rourke said.

The survey showed that landslides had torn sections of the pipeline from their concrete supports, and bridges carrying the pipe across rivers had been wrecked by flood waters and debris. Six miles of line were destroyed and breaks occurred in at least eight places along another ten-mile section. Other parts of the line were displaced. The costs of rebuilding plus the loss of oil revenues are expected to amount to $1 to $1.5 billion, O'Rourke said. This makes the Ecuador disaster the largest single pipeline loss in history.

3. Oil and gas (white) pipelines were deformed and exposed near an eroded river bank and a debris slide.

4. At the El Salado pump station the main crude-oil storage tank was ruptured. Note the distress of adjacent smaller tanks.

5. Esteban Crespo (at right) of the Cornell team inspects damage to the water tank (for fire protection) at the El Salado pump station. Note the separation of line from the emergency pump.

6. This collapsed building in Baeza was constructed of masonry and unreinforced concrete. The more modern concrete structure in the background was not damaged.

5

6

Figure 3

Figure 4

severe plastic deformations imposed by earthquakes.

In other work we have focused on jointed pipelines, which are commonly used in water-distribution systems. Analytical models that have been developed allow engineers to predict the probable behavior of the joints. This kind of modeling, which is based on stochastic finite-difference formulations, can take into account uncertainties in the mechanical characteristics of joints, as well as the interaction between pipelines and the surrounding soil.

THE SAN FRANCISCO CASE STUDY

The systems approach to lifeline engineering has been pursued in our research by modeling and by studying the performance of actual water supply networks. San Francisco was chosen for a special case study, and the work is being carried out with the cooperation of the city's fire and the water departments. Dames & Moore, consulting engineers in San Francisco, have made important contributions by characterizing the fire hazards following a severe earthquake.

San Francisco was the subject of a case study by Cornell researchers investigating the hazards caused by earthquake damage to lifelines.

Figure 3. The San Francisco fire that broke out after the 1906 earthquake destroyed more than four square miles of the city. This photograph was taken from Duboce Park; the dome of the city hall is in the background to the left. Fire-fighting was severely hampered by ruptures in water pipelines. (Photo courtesy of the San Francisco Public Library)

Figure 4. Permanent ground deformation was caused by the earthquake. This photograph shows seven feet of lateral offset on Valencia Street—the result of soil spreading caused by the liquefaction of underlying sediments. Line B-B_1 marks the original position of the trolley rail.

The ground movement ruptured two large pipelines, emptying 14 million gallons of water from the College Hill Reservoir and thereby depriving the city of a critical fire-fighting resource. This single event may well have been the most disastrous failure caused by the earthquake. (Photograph from a report by H. Schussler, chief engineer of the Spring Valley Water Company)

Figure 5

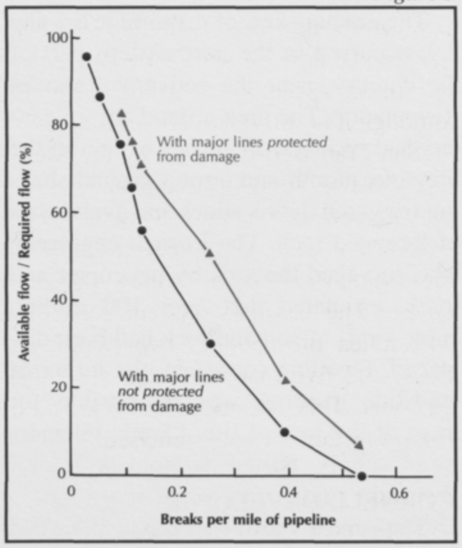


Figure 5. Computer-simulation data for San Francisco's auxiliary water system show how damage to pipelines would affect the supply of water available for fire-fighting, and how protective measures could improve the situation. The available water flow, expressed as a percentage of what would be needed for fire protection, is plotted as a function of pipeline breaks caused by seismic ground waves. The plot shows the mean values obtained from eighty computer runs.

San Francisco is well suited for such a study. After the 1906 earthquake, ruptured water pipelines and subsequent fires resulted in the largest single earthquake-related loss in United States history. More than four square miles of the city burned, destroying 490 city blocks and causing partial destruction of thirty-two additional blocks (see Figures 3 and 4). The geotechnical hazards in San Francisco include soils susceptible to liquefaction, landslides, and settlement. Approximately 85 percent of the water-distribution network is composed of cast-iron pipelines, and therefore is typical of many midwestern and eastern cities where earthquake damage should be an important aspect of planning for disaster relief, although it is still relatively unstudied.

San Francisco is served by the Municipal Water Supply System and by the Auxiliary Water Supply System, which was established to protect those areas most severely damaged by the 1906 earthquake. The auxiliary system comprises 115 miles of pipeline, two pump stations, and five manifolds that serve one fire boat. This system is the backbone of fire protection for San Francisco.

CORNELL-DEVELOPED COMPUTER SIMULATION

Computer models developed at Cornell simulate the post-earthquake operation of both of the San Francisco water systems. The model for the auxiliary system has been checked successfully against special fire-flow tests run by the fire department.

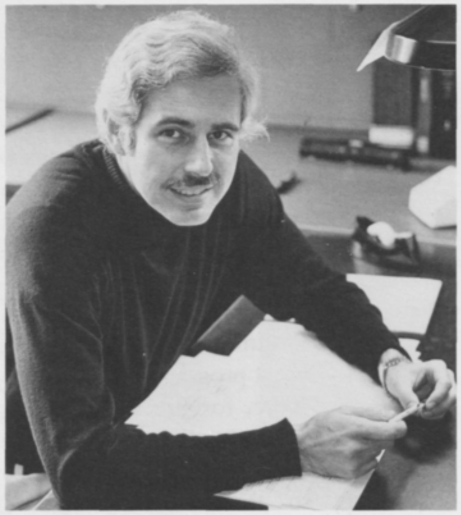
This computer model is built around a hydraulic-pipeline-network program that has been modified so as to allow the simulation of possible post-earthquake damage states. Pipe breakage caused by traveling ground waves is assumed to occur as a Poisson process, and is calibrated according to pipe-damage statistics from preious earthquakes. For permanent ground movements, the likely locations of pipeline breaks are established by means of subsurface surveys and studies of geotechnical site characteristics. The computer model assesses the water flow and pressure at critical hydrants and compares these with estimated demands in the event of fire. These estimates are generated by a probability-based program, developed by Dames & Moore, for fire initiation and spreading. The hydraulic-network model can simulate pump stations and fire-boat manifolds so that a full range of emergency-response options can be explored.

Figure 5 shows the results of a series of computer simulations for the auxiliary water-supply system, presented in the form of a fragility curve. The total available flow after an earthquake is expressed as a percentage of that needed to fight fires, and plotted as a function of the pipe breaks per mile of line. System improvements were explored with the computer model by incorporating special protective measures in large-diameter mains near reservoir locations. Although these mains account for only 5 percent of the system, the protection resulted in considerable improvement, as shown in the figure. For example, for a damage ratio of approximately 0.3 breaks per mile, which was observed for the 1906 earthquake, it can be seen that protection focused on a crucial 5 percent of the pipelines results in a 50 to 75 percent improvement in system performance.

Simulations and plots of this kind help in the choice of maintenance strategies and the planning of emergency response. Given the rapid development in

"The systems approach to lifeline engineering has been pursued in our research by modeling and by studying the performance of actual water supply networks."

O'Rourke



Grigoriu

computer technology, the simulation approach holds promise as a major tool for utility improvement. Moreover, the combination of pipeline instrumentation and computer simulations of damage could help to create a "smart" system, in which instrument feedback of flow and pressure loss is checked against system models to provide the most likely scenario for dispatching engines and repair crews immediately after an earthquake.

A BROAD EFFORT WITH NATIONAL SIGNIFICANCE

Because of the complex and interdependent nature of lifelines, research should be multidisciplinary, drawing on the expertise of specialists in areas including systems, seismology, and geotechnical, mechanical, and structural engineering. The new National Center for Earthquake Engineering Research will be able to draw on and coordinate many different disciplines for a comprehensive program on lifeline systems. Cornell will play a key role in these activities. Cornell researchers are already involved in cooperative projects with Japanese and Mexican investigators as part of a broad program sponsored by the center.

Of special national importance will be an emphasis on the performance of lifeline systems typical of eastern and midwestern cities in the United States. Many of these cities are vulnerable to severe earthquakes, yet their lifeline systems are old and ill-suited for major seismic disturbances. Ongoing Cornell work in this field, carried out in conjunction with the new research center, can make a substantial national contribution by identifying cost-effective programs of maintenance and emergency response that will fit naturally within the rehabilitation programs needed for older municipalities.

Professors Thomas D. O'Rourke and Mircea D. Grigoriu are members of the Department of Structural Engineering in the School of Civil and Environmental Engineering at Cornell.

O'Rourke came to Cornell in 1978 after three years on the teaching and research staff at the University of Illinois at Urbana, where he received his doctorate. He holds the B.S.C.E. degree from Cornell. O'Rourke has extensive experience in underground construction, as well as pipeline and foundation engineering. He worked for the British Transport and Road Research Laboratory in 1977–78, and has been a consultant to government, industry, and engineering firms. He received the C. A. Hogentogler Award from the American Society for Testing and Materials for his work on field instrumentation for large construction projects, and the Collingwood Prize from the American Society of Civil Engineers for an outstanding paper.

Grigoriu came to Cornell in 1980 after several years of professional practice and research in Romania, Venezuela, Canada, and the United States. He holds the Dipl.Ing. from the Bucharest Institute of Civil Engineering, the Dipl.Math. from the University of Bucharest, and the Ph.D. from the Massachusetts Institute of Technology. His research interests are in the fields of structural dynamics, structural analysis, fatigue, wind loads, and offshore platforms.

UNDERSTANDING THE SEISMIC RESPONSE OF STRUCTURES

The Role of Experimental Research

by Richard N. White

The motion of the earth during an earthquake is transmitted to any structure supported on layers of soil or rock. The structure, with its appreciable mass and stiffness, wants to remain stationary but cannot: the entire structure and its contents begin to move in a complex manner, and the resulting accelerations produce forces that can exceed the strength of the structure.

What happens depends upon the severity of the motion. The structural response may be linear and elastic, with essentially no stresses above the yield strength of the primary structural material. Or it may be highly inelastic and nonlinear, with considerable overstressing of materials, cracking and crushing (in concrete or masonry), and redistribution of load-resisting paths.

The results are not necessarily all bad: during the shaking process, the stiffness of the structural system may decrease by a factor of up to five or more, and this decreases the magnitude of seismic forces on the structure.

How can structural engineers predict what will happen to a structure as the result of an earthquake?

One approach is mathematical modeling. But in spite of tremendous advances in computer-based dynamic structural analysis, mathematical modeling cannot yet capture the exceedingly complex behavior of a typical building or bridge as it resists the motions and forces of a sizable earthquake.

In a reinforced-concrete structure, for example, the concrete will crack from both bending and shear effects, the bond action between steel reinforcing bars and the concrete will degrade from the high-intensity cyclic forces and permit internal deformations to develop, the reinforcing bar strains may reach many times the yield strain capacity of the steel, and the concrete may even crush in certain locations. Steel and timber structures do not exhibit as many nonlinear phenomena, but they do have their own complexities (particularly in connections) that are difficult to model. The presence of masonry walls, either plain or reinforced, greatly complicates the overall system behavior because of the cracking and changes in stiffness of the walls.

The analysis problem is not merely one of predicting stresses. Even more important is the ability to predict two other parameters: displacements at selected locations over the height of the structure, and the degree of ductility needed to maintain structural integrity at locations where large inelastic strains are experienced.

The alternative to computer-based analysis is physical experiment; and at the present time, experiments are essential for assessing structural performance under earthquake-induced forces. Some of the results are directly useful in design, but more often they are either generalized into building-code format (in which highly simplified models of structures are specified, with static lateral forces to represent earthquake loads), or are used to help develop, refine, and calibrate computer-based dynamic analysis procedures.

An important report published in 1984 by the Earthquake Engineering Research Institute (EERI)[1] assesses the experimental research that is needed to facilitate improved design of earthquake-resistant buildings.

The report identifies three categories to be considered: new construction, the strengthening of existing buildings, and the repair of earthquake-damaged buildings. The need for experimental research is examined for a range of building types: high-rise, intermediate-height, and low-rise commercial, residential, and industrial. The report calls for a massive new effort to develop adequate understanding of structural response to seismic forces, and to develop design procedures that will ensure a consistent and quantifiable level of risk.

A major four-phase feasibility study of a proposed National Earthquake Engineering Experimental Facility is currently being carried out by the National Research Council. This study is addressing technical matters such as those I discuss here, and also the fact that the United States is far behind Japan and other countries in the use of large-scale structural testing facilities for studying seismic effects.

STRATEGIES IN SIMULATING SEISMIC LOADINGS

Ground motion during an earthquake has a random nature that is most often resolved into horizontal and vertical components of acceleration, velocity, and displacement. The other major parameters are frequency content and duration of shaking.

Not only is the characterization of potential ground motion difficult in itself, but decisions are further complicated by the need to assess the hazard of various kinds of motion. As the EERI report expresses it, "we currently do not know with certainty what earthquake ground motion parameters cause what kind of damage." Different types and sizes of structures are sensitive to different parameters, and test engineers must be able to capture the significant parameters when they design testing equipment and experiments.

Figure 1

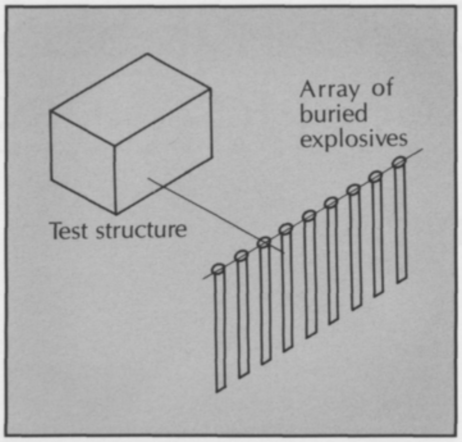


Figure 1. One method of testing the seismic response of full-scale structures is to measure the effects of underground detonations.

Some understanding of geometric scaling (similitude) is needed in discussing alternate testing strategies. Galileo was perhaps the first to recognize the subtle relation between self-weight stresses and size: that is, if the material density is held constant, self-weight (or dead load) stresses increase linearly with uniformly increasing dimensions. For example, expanding all the dimensions of a structure by the factor of 10 will increase self-weight stresses in all columns, beams, etc. by the same factor of 10. This relationship means that reduced-scale structures will have a large "deficit" of mass, and since earthquake forces are generated as the product of mass and acceleration, it becomes necessary to add mass to a model structure built of the same material as the full-scale (prototype) structure. While it may appear at first glance that increasing the acceleration would accomplish the same thing, actually it cannot provide the correct combination of dead load and seismic forces, nor can increased acceleration necessarily be accomplished from a technical standpoint, since the time scale of motion is also compressed in reduced-scale modeling.

Several loading strategies are presented here for structures ranging in size from full-scale to small-scale models. The EERI report contains detailed treatments of each of these strategies.

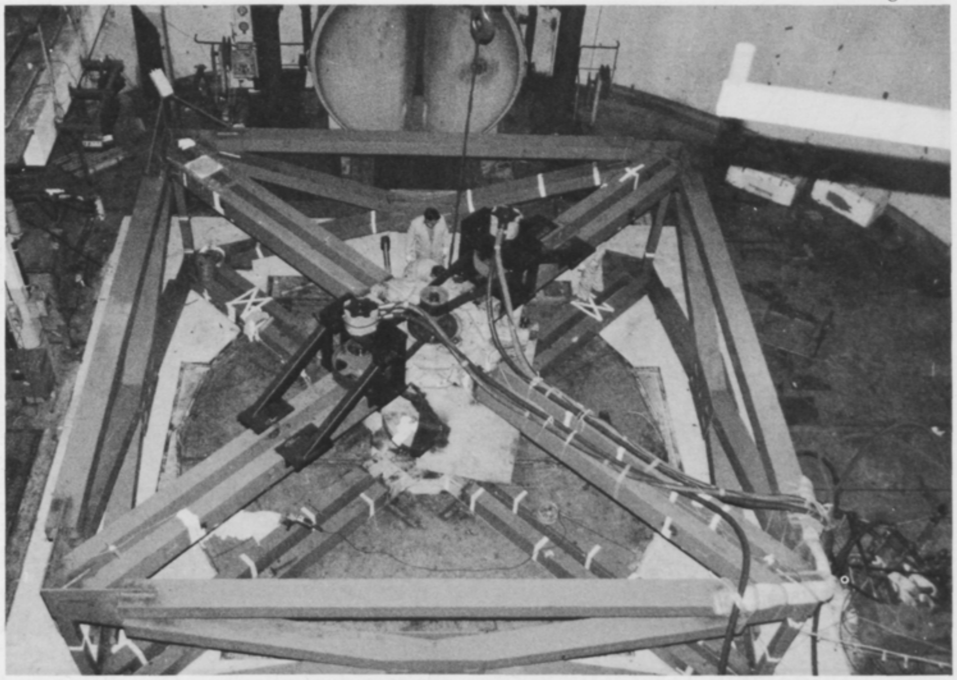
STRUCTURAL TESTING AT FULL SCALE

Full-scale tests are attractive in that similitude is satisfied automatically, interaction with the base soil can be provided, actual construction details (such as connections) are used, and the effects of partitions and other architectural components can be evaluated. The obvious problem is how to impose a sizable seismic loading on the structure.

A method that taxes our patience, yet is of critical importance, is to instrument existing buildings and then measure response during subsequent earthquakes. More than four hundred buildings in the United States are instrumented with accelerometers to determine seismic response. In an area of strong seismicity, test structures can be used to address specific research questions; in Japan, several types of building framing (strong beam–weak column, and strong column–weak beam) have been incorporated into test structures that have already experienced many moderate earthquakes. In all these "natural experiments", however, the waiting period for a large destructive earthquake is a serious shortcoming.

Another full-scale testing method utilizes high-explosive charges buried in the ground adjacent to the structure (see Figure 1). Properly designed and sequenced

Figure 2



explosive charges can produce ground motions with earthquake-like properties. Furthermore, the method permits high-intensity excitation of the structure, its foundation, and the surrounding soil mass. Although suitable techniques have been developed only recently, and therefore applications have been quite limited, this special loading method should become more widely used.

Considerable information can be obtained from full-scale testing even if the loading is not intended to simulate seismic motions. In this kind of experiment, mechanical means are used to provide the dynamic loading, which is usually either harmonic or pulsed, and determinations are made of the displacement-time history, the natural period of vibration, and the damping characteristics.

In the procedure illustrated in Figure 2, a rotating dual-mass vibrator is attached to the structure and run at various frequencies. Pulses can be applied in several ways. For example, rockets, gas pulsers, or mechanical metal-cutting devices can be attached to the structure and then activated. Alternatively, the structure can be dynamically excited by pulling it against another structure or a dead-man anchor, and then releasing the pulling force suddenly. The ambient vibra-

Figure 2. Another dynamic full-scale testing method is to subject the structure to mechanically produced vibrations, as in this MK-16 eccentric-mass vibrator at ANCO Engineers of Culver City, California. The figure near the center gives an idea of the size of the machine, which has a maximum force of 4 million pounds and a frequency range of 0 to 10 hertz. In one test it took an entire nuclear plant containment structure to 1 g.

"...at the present time, experiments are essential for assessing structural performance under earthquake-induced forces."

Figure 3

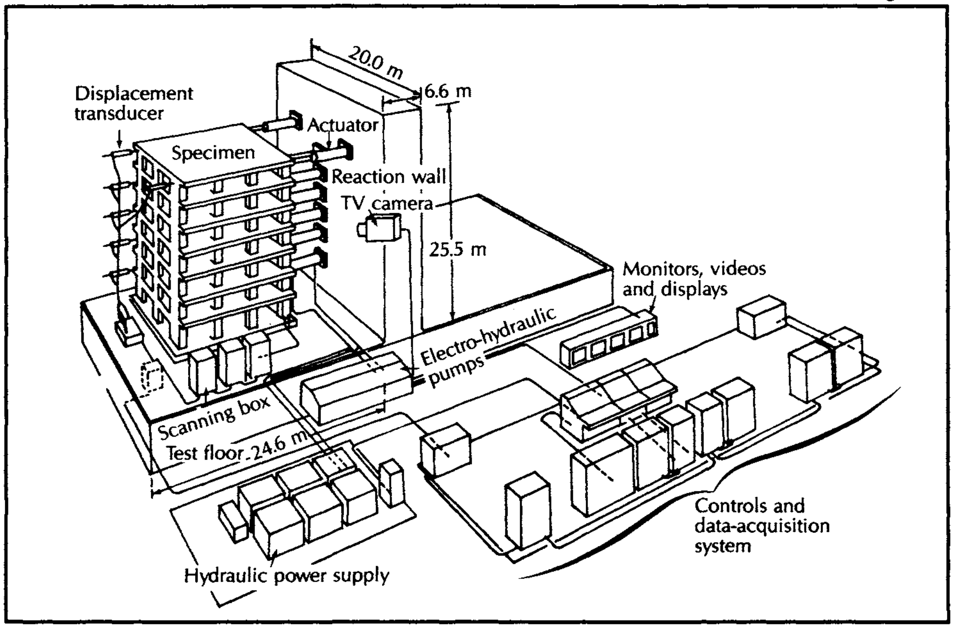


Figure 3. This pseudo-dynamic testing system at the Building Research Institute in Japan applies cyclic, static forces to full-scale buildings. Actuators between the structure and a reaction wall apply reversing horizontal forces at each story.

tions of wind loading are also useful in measuring the dynamic properties of a structure. These various nonseismic dynamic tests are particularly helpful in developing analytical modeling methods. They are useful too for studying —through comparisons of "before" and "after" measurements—the changes in a structure's stiffness and vibrational period caused by an earthquake.

Still another full-scale (or large-scale) method involves the application of cyclic, static forces that are intended to represent earthquake action. Typically, large hydraulic actuators are positioned between a structure and a massive reaction wall. An example is the test system at the Building Research Institute in Tsukuba, Japan (Figure 3). In this facility, several full-scale six- and seven-story buildings have been loaded to failure with reversing horizontal forces applied at each story level. In this type of testing, controlled displacements (rather than forces) are often imposed. In the more sophisticated systems[2], results are analyzed on-line and the actual restoring force characteristics of the structure (rather than pretest predictions) are used to decide how much displacement to impose at each floor. This approach, called pseudo-dynamic testing, is becoming increasingly popular, although experimental errors and the analytical extrapolation procedures have proven to be more troublesome than expected.

Full-scale testing of structural components, particularly beam-column connections, is also carried out by using hydraulic actuators to apply reversing static forces or displacements comparable to those expected during earthquakes. A drawback is that the test of a component often cannot capture the behavior of such a component in a complete structure because the properties of the building change during an earthquake. Tests of components do have the advantage, however, of utilizing precisely known forces and displacements. This greatly facilitates the unambiguous use of results in developing computer analysis software, and it helps in drawing up improved building-code provisions.

Another consideration is that it generally costs less to test components than to test full-scale structures, especially in view of the lower initial expense of setting up the laboratory.

THE EFFECTIVENESS OF REDUCED-SCALE MODELS

Reaction-wall and component-testing methods can also be used to great advantage with reduced-scale models. Research conducted in our Structural Models Laboratory has shown the excellent correlation possible between full-scale and 1/10-scale models. Figure 4, for example, summarizes a comparative study of the actual and predicted behavior of a reinforced-concrete beam-column joint under reversing cyclic loads that go far beyond the yield strain capacity of the reinforcing steel.

Figure 4

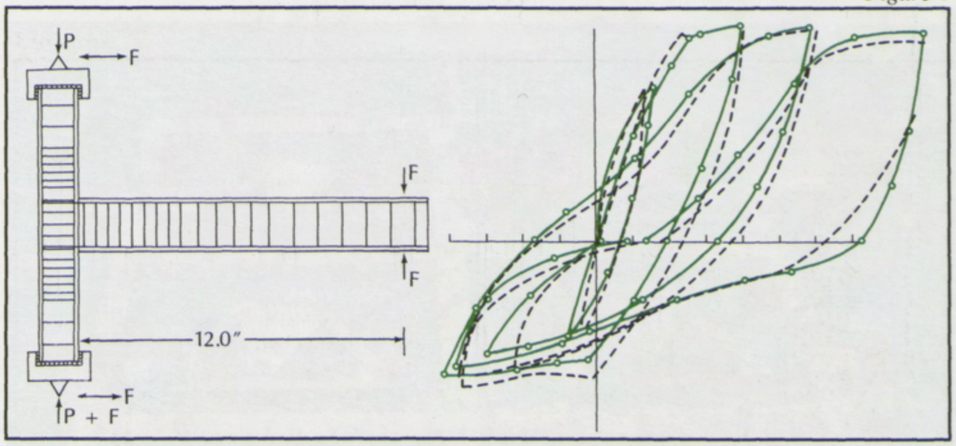


Figure 4. Scale-model testing can give reliable results, as demonstrated by these data obtained in Cornell's Structural Models Laboratory. The black lines represent measurements of the moment-rotation response of an actual joint connecting a beam and a column, both made of reinforced concrete. The lines in color represent values predicted from measurements of a 1/10-scale model.

Laboratory simulation of earthquakes with hydraulically driven shaking tables has been one of the most popular methods for dynamic testing of civil engineering structures since about 1970. Typical shake tables can be driven both horizontally and vertically with motions that duplicate the histories of actual (or hypothetical) earthquake ground motion. One of the most modern shake tables in the world is the 12-by-12-foot table at the State University of New York at Buffalo (see the photograph on the inside front cover). This table has capabilities for rocking and torsional motions, as well as vertical and horizontal motions.

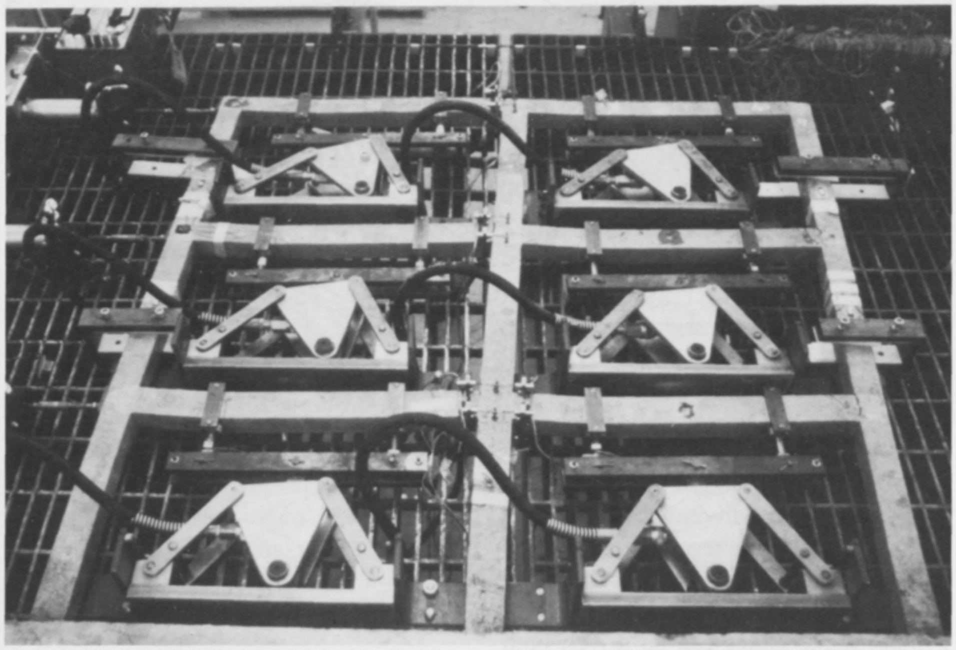
Except for a 50-by-50-foot table in Japan and an even larger one in the Soviet Union, existing shake tables are too small for full-scale testing; therefore, reduced-scale testing is necessary. The associated problems include mass scaling, reproduction of detailed phenomena such as cracking and bond in reinforced-concrete structures, connection fabrication, and miniaturization of measuring devices. In spite of these problems, we have excellent data from the testing of model structures on shake tables all over the world. The technique has enabled researchers to make major advances in understanding the complex behavior of real structural configurations subjected to seismic motions.

EXPERIMENTAL RESEARCH AT THE NEW CENTER

A number of projects in which structural experiments are a major component are part of the program of the new National Center for Earthquake Engineering Research (NCEER), which has been established as a cooperative venture at several locations in New York State. These projects include:

- *Protective systems and retrofit of building structures for mitigation of earthquake hazard.* Engineers from six universities are investigating passive and active control devices to reduce the energy transferred from ground motion into the structure. The SUNY/Buffalo shake table will be a central facility for many experiments involving tuned mass dampers, earthquake barrier systems, friction- and energy-dissipating systems, base isolators, and devices to apply forces counter to those created by earthquake motion.
- *Seismic performance of secondary systems.* In a structure, a secondary system is usually a relatively light appendage that receives seismic motion from the more massive primary system. Secondary systems such as critical electrical and mechanical equipment will be studied experimentally and analytically.
- *Viscoelastic dampers for seismic applications.* This project involves investigators from SUNY/Buffalo, the University of California at Berkeley, and the 3M Company. Viscoelastic dampers will be inserted into a 1/4-scale model of a prototype structure and tested on the SUNY/Buffalo shake table, and a 1/3-scale model steel structure will be similarly modified and tested on the Berkeley shake table.
- *Dynamic analysis and testing of structures and structural components under seismic loads.* This project has three phases. The one involving Cornell is discussed below. Another is a joint project at SUNY/Buffalo and Lehigh University on the seismic response of buildings with flexible floor diaphragms. (Designers often assume that a floor system is infinitely rigid, but in reality it may have

Right: In Cornell's Structural Models Laboratory, earthquake stress is simulated in tests of this 1/10-scale model of a three-story, two-bay reinforced-concrete building frame. The model is subjected to gravity loads and reversing lateral loads to simulate seismic action.

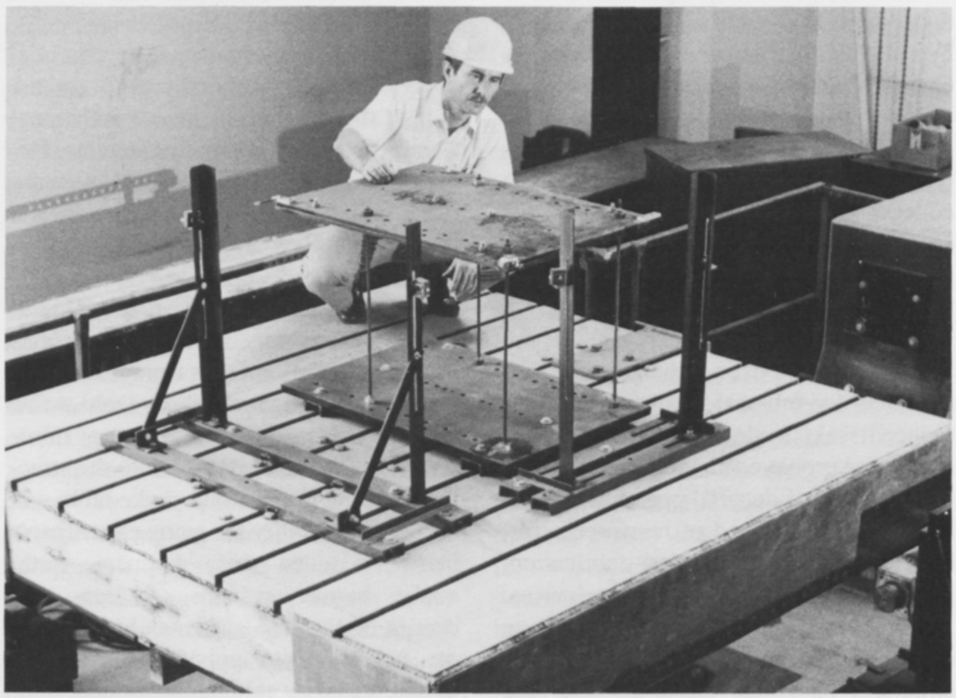


enough flexibility to be important in the building's resistance to seismic loads.) The third investigation, at Rice University, will be a study of the strength and load-deformation behavior of repaired beam-column and slab-column connections in reinforced-concrete buildings. Specimens that have been tested to nearly total collapse under simulated seismic loading will be repaired and retested to gain a better understanding of how repaired structures can carry subsequent heavy loadings, including earthquakes.

CORNELL COMPONENTS OF THE NCEER PROGRAM

At Cornell Peter Gergely and I are heading a research group working on several important problems that require experiments on structures.

One of our projects, being carried out jointly with SUNY/Buffalo and Lehigh University, is concerned with the safety of existing reinforced-concrete structures in regions of moderate seismicity, such



Right: This shake table in the George Winter Structural Research Laboratory at Cornell is being upgraded for use in experimental projects of the new National Center for Earthquake Engineering Research. Shown with the table is Professor Peter Gergely.

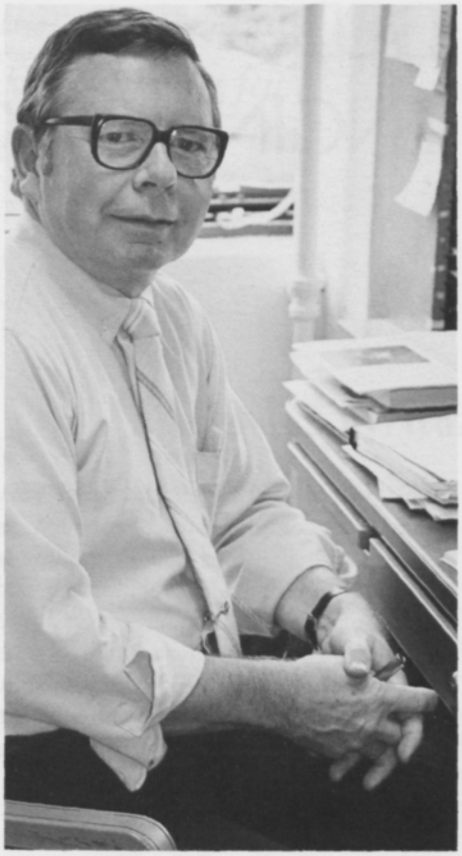
as parts of the eastern United States. The columns in these buildings tend to have small amounts of both primary and secondary (transverse) reinforcement, with reinforcing bar splices occurring directly above floors in locations of potentially high bending action during earthquakes. We are embarking on a series of experiments on 2/3-scale components to study column strength and ductility under reversing static loads of varying intensity.

As part of the same study, we will select existing reinforced-concrete buildings for detailed study of safety factors. Experiments will be conducted at various scales on those building components that are identified as being both critical to seismic resistance and not yet well understood. Test results will be used to help develop formal damage-assessment models and to improve the procedures for evaluating existing buildings.

In the other major project, the behavior of building models loaded on the shake table will be studied. The initial work will be on reinforced-concrete buildings, but we may also test small models of steel buildings as part of a cooperative program between NCEER and researchers in China. We are now upgrading our table in the George Winter Structural Testing Laboratory, and are also developing improved modeling materials.

A PROGRAM WITH SCOPE AND GLOBAL SIGNIFICANCE

The laboratory test programs of the NCEER have a broad scope. They will provide information about the safety of structures during earthquakes and about the levels of damage that might be caused by various types of seismic motion —information needed for developing sophisticated dynamic analysis programs,



code improvements, and expert-system tools (discussed in the article in this issue on computer-aided earthquake engineering). At the present stage of knowledge about earthquake hazard, experiments are essential. And since such experiments require sophisticated and expensive equipment, the pooling of resources and funding makes possible an ambitious research program.

The new center opens up opportunities for research that will be pertinent not only to New York State, where the center is located, but to the Northeast, the nation as a whole, and the world. Seismic risk is a global problem.

At Cornell Richard N. White is a professor of structural engineering in the School of Civil and Environmental Engineering and, beginning in July, the associate dean for undergraduate programs at the College of Engineering. He has served as director of his school.

A specialist in model analysis and concrete structures, White is currently the lead principal investigator in two programs of the National Center for Earthquake Engineerng Research. He is a co-author of four books on structural engineering, and is senior co-editor (with Charles G. Salmon of the University of Wisconsin) of the 1197-page Building Structural Design Handbook, *published this spring by Wiley. He is a fellow of the American Concrete Institute and of the American Society of Civil Engineers, and a recipient of the ASCE's Collingwood Prize.*

White holds B.S., M.S., and Ph.D. degrees from the University of Wisconsin. Before joining the Cornell faculty in 1961, he worked for a firm of consulting engineers in Madison, Wiscoinsn, and served in the United States Army Corps of Engineers. He is a registered professional engineer in New York State.

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COMPUTER-AIDED EARTHQUAKE ENGINEERING

by John F. Abel and William McGuire

There is no such thing as a linear structure. This is a maxim in structural engineering that is sometimes demonstrated with devastating results during earthquakes.

With a *linear structure*, the physical response to a given load—such as a seismic disturbance—would be elastic and first-order (that is, the deflections would be small enough to be neglected in the mathematical expression for equilibrium) and therefore its calculation would be straightforward. Structures don't behave strictly like that, however; *nonlinear* effects may be significant. Second-order elastic effects ("corrections" for large displacements and rotations) contribute to the response of tall buildings to wind, and of long-span suspension bridges to truck traffic, for example. More extreme loadings also cause inelastic nonlinearity such as yielding and fracturing. If the force is an earthquake, the response of a building could be collapse.

The need for consideration of nonlinear behavior in seismic structural design is a central concern of the new National Center for Earthquake Engineering Research, which is located at a group of institutions, including Cornell, in New York State. For complex structures such as buildings, the estimation of nonlinear effects requires high-level computing, and so one of the center's main objects is to explore and develop ways of applying the latest computer technology to seismic problems. Researchers at Cornell are actively engaged in all phases of this research.

THE THREE-PART CORNELL PROGRAM

Computer-aided earthquake engineering requires the integration of many new and developing computer technologies. It involves engineering workstations, supercomputing, and networking, and requires such tools as interactive graphics, algorithms, and numerical modeling. At Cornell we have established a program in this field with three interrelated areas of study.

First and foremost is the design, redesign, and/or evaluation of structural systems. This entails determining whether structural schemes are safe (as well as functional and economic) and, if they are not, determining what changes are necessary to make them appropriately strong or stiff. The computer methods used are both *algorithmic* (using a specific procedure to carry out a specific calculation) and *advisory* (relying on so-called expert systems, based on prior knowledge).

The second concern is the advancement of computer-simulation techniques. Improved methods will aid in analysis and design, and support research into the behavior of structures.

The interplay among theory, experiment, and field observation in the development of new techniques and models is the third subject of study. This interplay is reciprocal; for example, experiments and observations are needed to verify computer models, while simulations can be used to help design experiments

Our current efforts are concentrated primarily on buildings in order to restrict the work to a manageable scope. Because of the geometric and behavioral complexity of buildings and their components, interactive computer graphics is essential not only for visualization of simulations and designs, but also as a medium of two-way communication between the engineer and the computer. The use of graphical

"Almost all structural failure is preceded by substantial nonlinear behavior, a fact that should be recognized in design."

tools is a common thread running through the work we describe here, and much of this work is being carried out within Cornell's Program of Computer Graphics, which is directed by Professor Donald P. Greenberg, a co-investigator on this project.

COMPUTER-AIDED ANALYSIS AND ALGORITHMIC DESIGN

Nonlinear behavior of structures is not usually obvious. Second-order elastic effects are generally small, and therefore precise observations are needed to detect them. Furthermore, an elastic structure returns to its original position after the cessation of loading. Material nonlinearities, in the form of inelasticity, result in permanent deformation, but these too are imperceptible in well designed structures under normal service loading. Such structures last for hundreds of years with no visible evidence of permanent distortion.

What may be all too obvious is the permanent deformation, including fracture, that constitutes structural failure. Almost all structural failure is preceded by substantial nonlinear behavior, a fact that should be recognized in design. This is particularly true in design for earthquake resistance.

Because the forces generated by a major earthquake may be so great that avoidance of any permanent damage would be enormously costly, a common approach is to attempt to prevent all but very minor damage under moderate earthquakes, and to ensure that the structure would not collapse under a major earthquake. A building, for example, might sustain substantial permanent damage, but the occupants could still be safe. Seismic design of this order requires some degree of nonlinear analysis, although in current practice it may be highly approximate—for example, the designer may use a single ductility factor to represent the energy dissipation due to nonlinear material properties.

Improving this design approach requires extensive knowledge of material behavior and advanced analytical capability. The problems are so complex that despite many years of research, much more effort is needed to achieve adequately realistic modeling. Cornell research on the nonlinear analysis and design of steel-framed buildings, sponsored by the National Science Foundation over the past seven years, provides an example. Although significant progress has been made on the development of practical, economical methods for static and dynamic nonlinear analysis and design through the medium of interactive computer graphics, neither we nor anyone else are yet able to simulate fully, in three dimensions and in all of its complexity, the response of even a ten-story building to gravity, wind, and earthquake. Figures 1 through 4 are glimpses of interactive simulations that are currently possible with a superminicomputer, but it should be noted that various approximations have been included in the modeling.

NEW CAPABILITIES THROUGH COMPUTER SIMULATION

The basic goal of our research in computer simulation is to develop unprecedented capabilities for modeling the nonlinear behavior of three-dimensional structures under seismic forces. For example, the type of analysis illustrated in Figures 1 through 4 is being extended to skyscrapers while at the same time being made more complete in terms of struc-

Figure 1

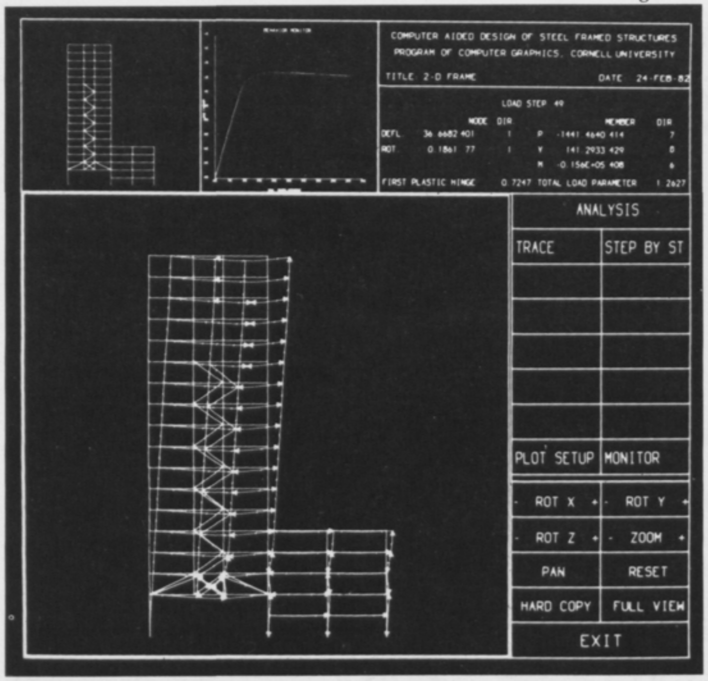


Figure 2

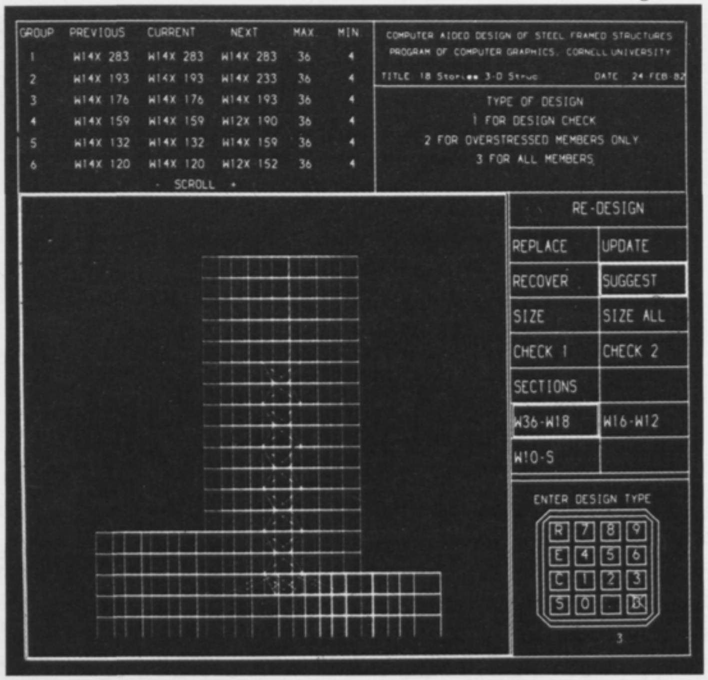


Figure 3

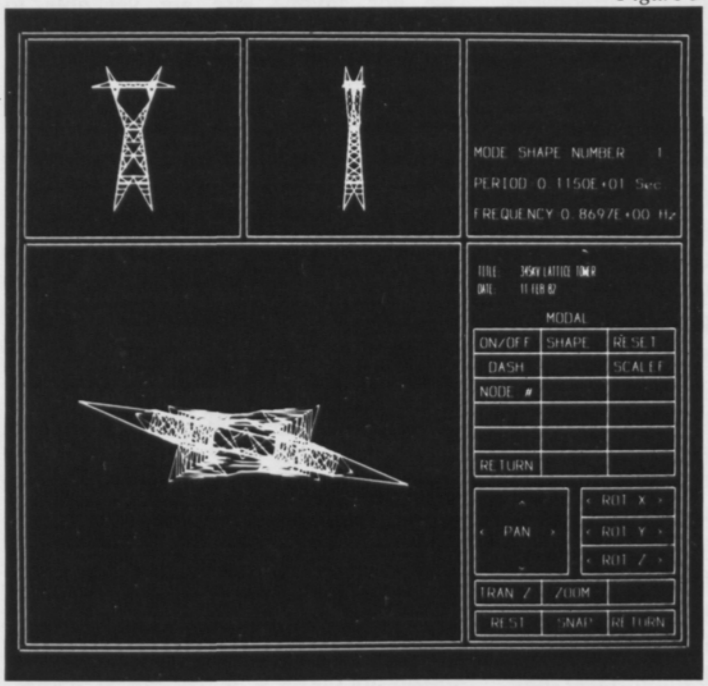


Figure 4

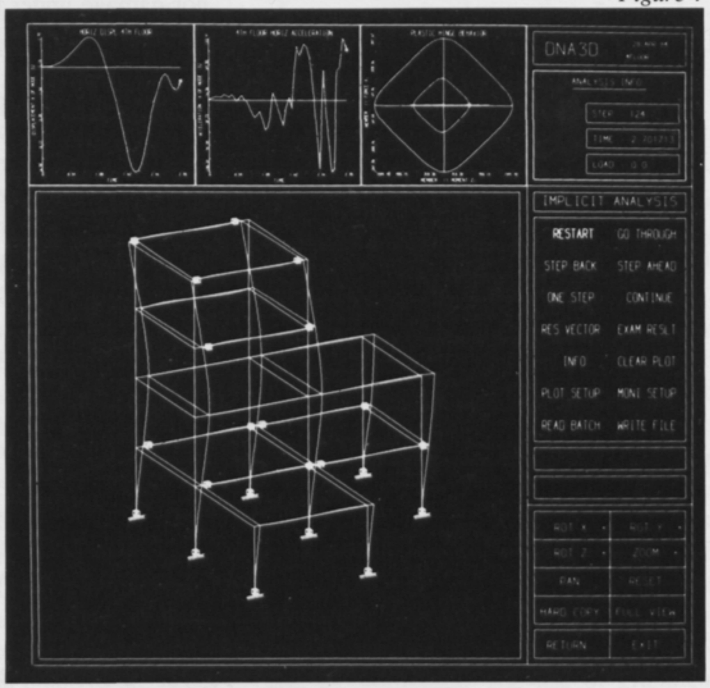


Figure 5

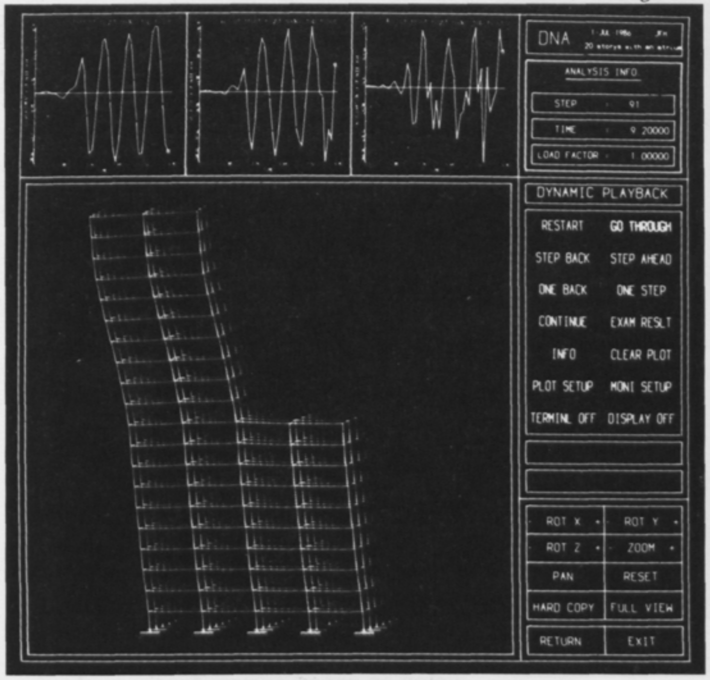
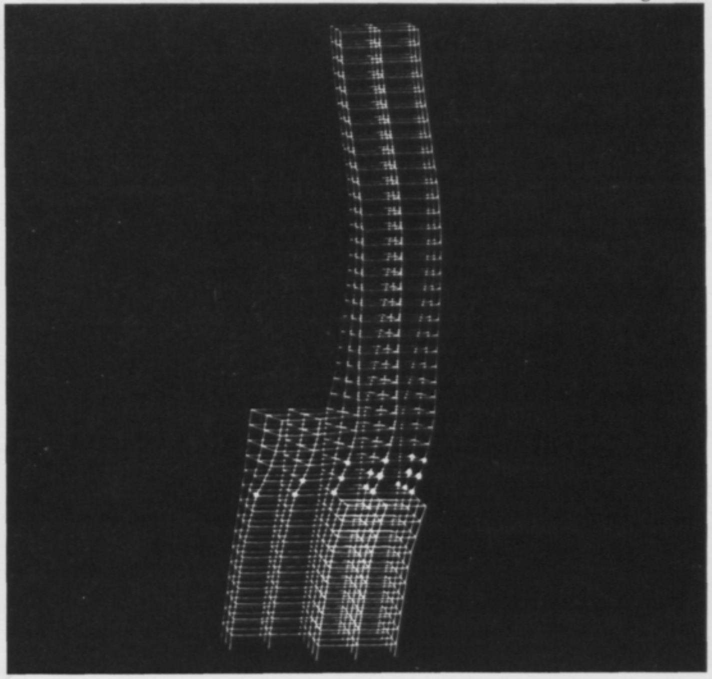


Figure 6



Above: Views from the nonlinear dynamic analysis of a twenty-story building (Figure 5) and a forty-story building (Figure 6).

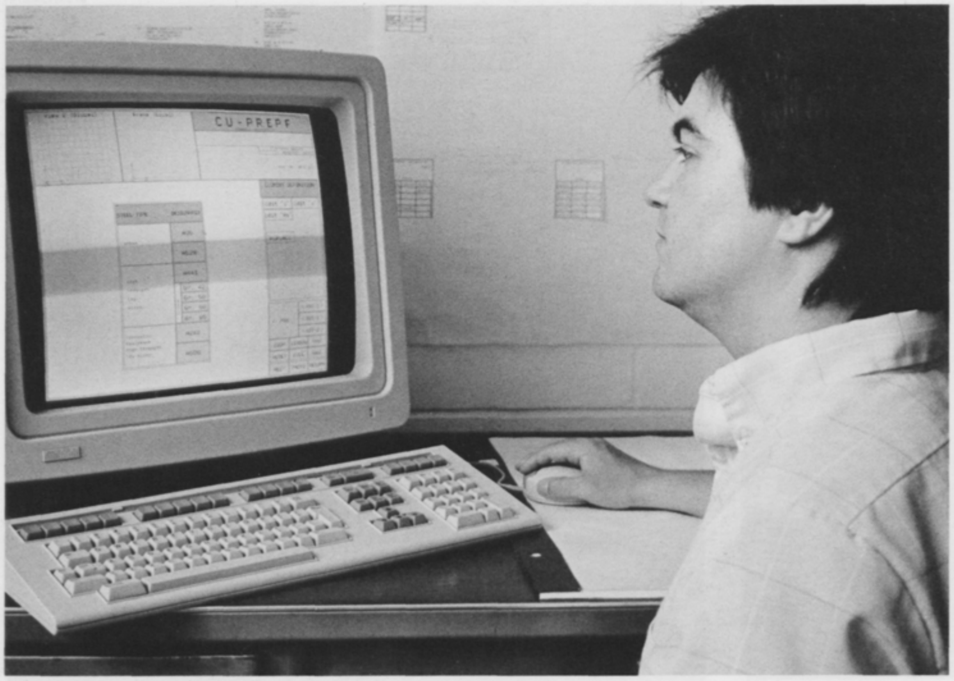
tural elements and behavior. In addition to being of direct use in design, the analytical tools and innovative computing techniques we are seeking will be of use in other analytical and experimental aspects of earthquake-engineering research.

Specifically, we are developing detailed finite-element models for the geometric and material nonlinear analysis of components of three-dimensional steel and concrete structures. For the modeling of steel structures, we will develop representations of the effects of residual stress, initial imperfections, spread of plasticity, nonuniform torsion, cross-sectional distortion, local buckling, and joint deformation. For concrete structures, the major questions to be addressed concern continuum modeling, the cracking of members, time-dependent effects, and interaction between steel and concrete.

On the basis of these detailed studies, we hope to prepare useful models for overall buildings that will incorporate features now generally excluded in even the most advanced calculations. These features include, for example, the actual resistance of surface cladding, interior partitions, and other "nonstructural" elements.

Advanced supercomputing and graphics facilities and capabilities are being marshalled to carry out this research. We are developing new algorithms, devising innovative graphical techniques for interactive control and visualization, and moving from an initial use of attached processors toward the eventual employment of massively parallel computers. Figures 5 and 6 illustrate the results of some of the early work in this direction. They are views of twenty- and forty-story steel-framed buildings that have been subjected to a full geometrical and material nonlinear analysis on an FPS 264 attached processor.

Opposite: Figures 1 through 4, photographed from superminicomputer displays, are examples of simulations made in the Cornell research program described here. Illustrated are: (1) nonlinear static analysis of a plane frame; (2) building-frame redesign; (3) transmission-tower vibration; and (4) nonlinear dynamic analysis of a four-story building.



“EXPERT SYSTEMS” BASED ON PRIOR KNOWLEDGE

Earthquake-resistant design of structures is based to a large extent on experience gained by observing the damage caused by earthquakes. Some of this knowledge, as well as information obtained from sophisticated dynamic analyses, is embedded in building codes. Much of the information, however, is not, and cannot be, included in codes.

One of our projects will entail the development of a knowledge-based expert system (KBES) for the preliminary structural design of buildings; the principal investigators are Professors Peter Gergely and John F. Abel. A KBES is an interactive computer program incorporating judgment, experience, rules of thumb, intuition, and other expertise to provide knowledgeable advice. Its two main distinct components are a knowledge base

To make research results accessible to practicing engineers, programs developed at Cornell are being transferred to interactive graphics microcomputers such as this MicroVAX II GPX workstation in Hollister Hall.

(a collection of rules) and a control or problem-solving technique (sometimes referred to as an inference mechanism).

The knowledge base for the current project is being collected primarily from reconnaissance reports written by specialists who have visited damaged areas after major earthquakes, and from recommendations by experts in earthquake engineering. During the first year, a preprototype system will be developed and several expert-system “shells” (or programming systems and inferencing mechanisms) will be evaluated for their suitability.

This project is coordinated with a companion investigation at Lehigh University (directed by Professors John Wilson and Peter Mueller) which concentrates on the architectural aspects of the preliminary design. The two expert systems will complement each other and may eventually be combined.

The key feature of these expert systems is that the input and output will be graphics-based; thus the programs will rely heavily on the latest advances made at Cornell in computer graphics for structural engineering. Furthermore, these expert systems will eventually be linked to sophisticated dynamic design and analysis programs, such as those described in the previous sections.

A third, related, project is in progress at Carnegie-Mellon University under the direction of Professors Stephen Fenves and Jacobo Bielak. Its purpose is to develop an expert system for the evaluation of existing buildings for earthquake hazards.

These expert systems will allow architects, structural engineers, and code officials to take advantage of a large body of expert opinion regarding the safety of various types of building.

TECHNOLOGY TRANSFER AND DISSEMINATION

The ultimate goal of all this research is, of course, to advance the state of earthquake-resistance design, enabling practicing engineers to prevent failures such as the collapse of buildings in the 1985 Mexico City earthquake. Although many of the Mexico City buildings had unacceptable characteristics such as poor construction and patently inferior design, some of the buildings that collapsed were designed and constructed in full accordance with accepted practice.

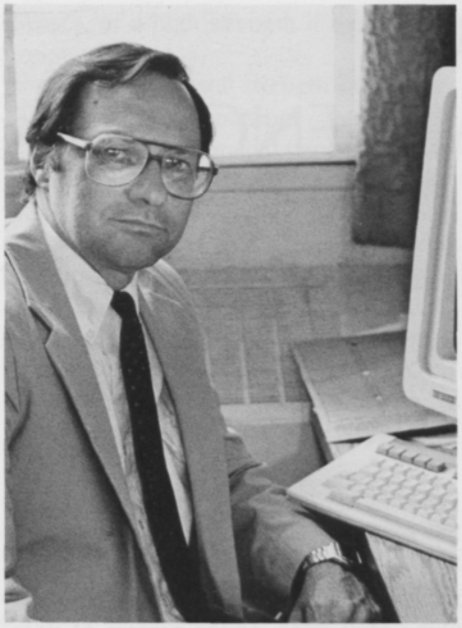
It is clear that if the same situation is to be avoided in the future, the products of "high-technology" advanced research now underway must be transferred to practice. Several things are being done or are contemplated to facilitate the dissemination of the Cornell research findings and to make them more useful to design engineers.

One of our intentions is to transfer as much as possible of the directly applicable research for use with the advanced interactive graphics microcomputer workstations that are becoming available. These workstations are being used in rapidly increasing numbers by researchers, students, and designers in engineering firms. As a first step, we are transferring the static and dynamic steel-frames programs that we developed in research over the past seven years to MicroVAX II GPX workstations. This coming August we will hold a workshop on these programs for practitioners and researchers.

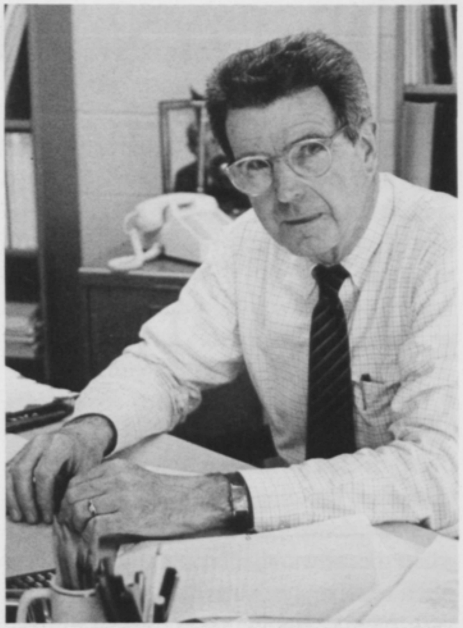
In addition, two workshops on expert systems are planned. The first, also scheduled for August of this year, will provide the opportunity for participants in the research projects mentioned above, and a few invited engineers, to exchange ideas and discuss plans. The second workshop, in 1988, will serve as a forum for the presentation of the prototype programs and an opportunity for invited architects and structural engineers to begin experimenting with the programs.

We are also initiating cooperative research with other analytical and experimental investigators associated with the National Center for Earthquake Engineering Research. We hope in this way to draw more people into this effort, and through them to broaden the influence of this line of research.

Abel



McGuire



John F. Abel and William McGuire are professors in the Department of Structural Engineering at Cornell.

Abel's research is concerned with the development of numerical approaches to problems in structural engineering and structural mechanics. McGuire specializes in research on the performance and design of metal structures. The development of methods using the supercomputer and adanced computer-graphics equipment is important in the research programs of both men.

Abel holds a baccalaureate degree in civil engineering from Cornell, a master's degree from Stanford University, and a doctorate from the University of California at Berkeley, and he is registered as a professional engineer. After completing his graduate work, he served for two years as a research engineer in the Army Corps of Engineers, taught at Princeton University for four years, and then joined the Cornell faculty in 1974. Currently he is a member of the executive council of the International Association of Shell and Spatial Structures and is active also in the American Concrete Institute and the American Society of Civil Engineers.

McGuire received the B.S. degree in civil engineering from Bucknell University in 1942, served in the navy during World War II, and earned a master's degree from Cornell in 1947. Before joining the Cornell faculty in 1949, he spent two years in structural engineering design practice, and is registered as a professional engineer in New York State.

He has written or co-authored two textbooks, lectured in New Zealand, Australia, Thailand, and Japan, and he has served as a consultant to a number of firms. At the present time he is a member of the specification committee of the American Institute of Steel Construction. A fellow of the American Society of Civil Engineers, McGuire has received that organization's Norman Medal, and also a Special Award from the American Institute of Steel Construction.

SOIL DYNAMICS IN EARTHQUAKE ENGINEERING

by Harry E. Stewart

Collapsed buildings, buckled bridges, and other evidence of structural damage are what the news media usually focus on when reporting earthquakes. The impression may be that the responses of timber, steel, stone, and concrete are the only considerations in earthquake analysis and earthquake-resistant design.

Actually, earth materials are a major factor. All constructed facilities are in some way founded on or in earth materials, and sometimes the structures—such as rock- and earth-fill dams—are constructed entirely of these materials. Since the soil is always present, it is difficult to separate earthquake damage, or prevention of damage, into components that are related entirely to a steel or concrete structure, or entirely to the supporting foundation materials.

The study of how soil and rock behave as engineering materials is known as *geotechnical engineering,* and it is this field of civil engineering that deals with soil dynamics. In this article I will discuss the role of soil dynamics in earthquake engineering, and introduce some of the concepts that relate to soil behavior under dynamic loading conditions.

HOW SOILS RESPOND TO EARTHQUAKE LOADING

The main source of earthquakes is relative movement between adjacent rock plates along fault lines, or the rupture of deep rock masses. These movements release energy and initiate a complex set of vibrations which are transmitted as traveling waves that spread throughout the rock masses and upward toward the earth's surface. The rate at which the waves propagate can be related to the elastic volumetric compressibility, the shear stiffness, and the density of rock and soil through which they travel. The motions resulting from the waves are dependent on the magnitude of the released energy and the dynamic properties—such as stiffness and damping—of the media.

As the traveling waves propagate upward, cyclic shear stresses develop within the soil. These cyclic stresses can lead to dramatic changes in the soil stiffness, which in turn can result in large ground movements under transient earthquake loading. For example, if the soil consists primarily of saturated granular materials such as sand, large soil movements are apt to result from changes in the soil strength brought about by repeated or cyclic earthquake loading.

Cyclic loading produces some responses in soil that are similar to those caused by static loading, but there are some significant differences. The behavior of saturated cohesionless sands provides an example.

When such sands are subjected to steadily increasing shear stresses, and if the drainage conditions are such that water can flow into or from the interparticle voids, the way the particles are packed tends to change, causing the soil to either contract or dilate. How the volume changes depends on the overall confinement and the initial physical state or density of the deposit. Generally, the hydraulic conductivity of sands is high enough so that the sand is said to be sheared in a drained condition when subjected to slow monotonic loading. The static strength of the soil is defined in terms of the maximum frictional resistance that can be developed for a given level of boundary normal stresses.

Earthquake loading produces a different response. Although the hydraulic conductivity of sandy soils is relatively high, the loading rate is also sufficiently high to keep the water from escaping—and if there is no drainage, there is no gross volume change. There is, however, a tendency for contraction, which causes the pore water pressure to increase. This affects the soil strength because strength derives primarily from frictional resistance, which is proportional to effective stress, and effective stress is the difference between the total normal stress and the pore water pressure. Since the total normal stress is not greatly affected by earthquake-induced cyclic shear stresses, the increase in pore water pressure results in a decrease in effective stress. In other words, the train of events begins with a transfer of gravity loading from the soil skeleton to the pore water; this reduces the effective stresses; and this increases the deformability and reduces the strength of the soil. It is a process that can lead to large foundation movements.

FACTORS AFFECTING THE STRENGTH OF SOIL

Cyclic soil strength, in comparison with static strength, is defined by a combination of the applied shear and the number of load cycles. During undrained cyclic loading, the applied stresses at each load cycle are generally less than the maximum shearing resistance, and the soil builds up residual pore pressure with each cycle. The rate at which the pore pressures increase depends mainly on the magnitude of the applied shear stresses. When these are low, many cycles are required to generate high pore water pressures and significant strength reduction; when the shear stresses are high, a small number of load cycles is enough. A given soil type may have a low cyclic strength under high applied cyclic stresses, or a high strength if the applied stresses are low.

A reduction in soil strength and consequent loss of supporting capacity can result in the dramatic and dangerous phenomenon called *soil liquefaction.* A commonly used definition of liquefaction is the soil state that results from the cyclic buildup of water pressure until the pore water pressure equals the total vertical stress, so that the effective stress is zero. At this point the soil would have no shearing resistance and would flow as a viscous fluid. This is not always possible under sustained cyclic shear stresses, however, so a more general definition of liquefaction, encompassing all the phenomena related to increases in pore water pressure and loss of strength, is often used.

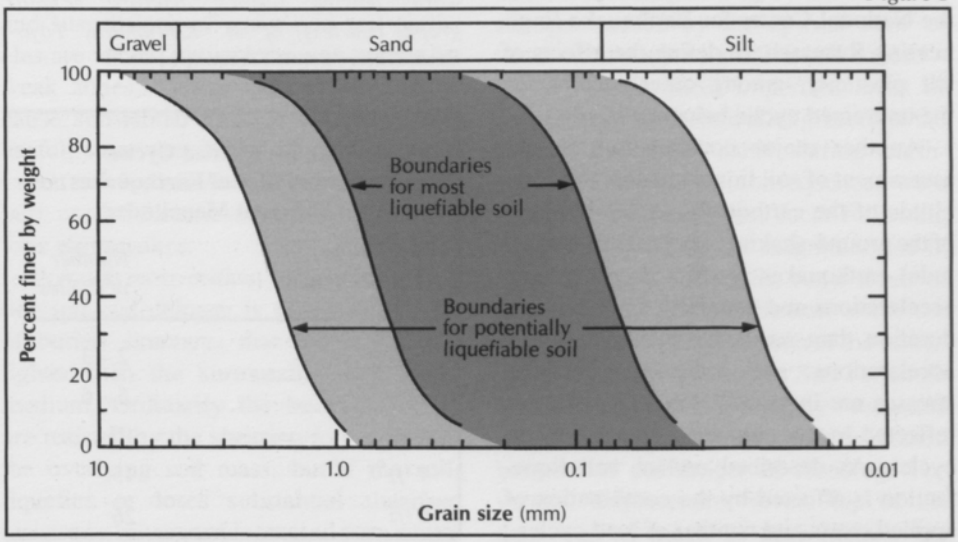
Figure 1. Approximate boundary curves show the influence of particle size on the tendency of soils to liquefy during earthquakes. The most sensitive soils are clean, uniformly graded sands having a median grain size of roughly 0.1 to 1.0 millimeter. (Source: Tsuchida, 1970.)

THE SUSCEPTIBILITY OF A SOIL TO LIQUEFACTION

One of the most important factors contributing to liquefaction susceptibility is the soil type. Clean saturated cohesionless soils, such as sands, are the most likely to liquefy during earthquakes. Figure 1 shows the general particle-size distributions of soils that are prone to substantial buildup of excess pore water pressures during earthquakes.

Uniformly graded sands, with median grain sizes roughly between 0.1 and 1.0 millimeter, are the most likely to generate excess water pressures and undergo substantial strength reduction. As the size distribution tends toward gravels, the permeability of the deposit increases dramatically, often by orders of magnitude. With clean gravels and some coarse sands, the excess pore pressures generated during ground-shaking may dissipate enough so that large changes in effective stress do not occur. (There may be enough volumetric distortion to cause unacceptable foundation settlement, however.)

Figure 1



The potential for soil liquefaction is also reduced as the grain-size distribution shifts from sand-sized toward finer particles. The behavior of fine-grained soils is controlled more by the plasticity of the fine fraction than by grain size, however. Saturated, loose silts with non-plastic fines have been known to liquefy, but the precise combination of properties that preclude liquefaction have not been defined fully. Investigations are underway at Cornell, through our participation in the National Center for Earthquake Engineering Research, to define the effects of silt plasticity, among other factors, on the undrained cyclic behavior of silts.

Another major consideration in the assessment of soil liquefaction is the magnitude of the earthquake, or the intensity of the ground-shaking. Large (high-magnitude) earthquakes produce larger ground accelerations and generally have a longer duration than small earthquakes. As the accelerations are increased, shearing stresses are increased; longer duration is reflected in the number of applied stress cycles. As described earlier, soil liquefaction is affected by the combination of applied stress and number of load cycles.

Figure 2

Figure 2. Sand boils such as these (about a meter in diameter) result from soil liquefaction. Pore water pressure causes water and suspended particles to be vented upward, leaving surface deposits. (Photograph courtesy of M. Kawamura, Toyohashi University of Technology)

Number of Load Cycles Representative of Earthquakes of Different Magnitudes

Magnitude (Richter scale)	*Number of Cycles*
5 1/4	2 – 3
6	5 – 6
6 3/4	10
7 1/2	15
8 1/2	26

The applied stresses are often computed by analytical methods based on either a theoretical maximum surface acceleration, or a measured acceleration history obtained from a previously recorded earthquake. The number of significant load cycles may be computed analytically, given a design acceleration history, or estimated on the basis of statistical correlations developed from previous earthquake data (see the table).

The confining stress within the deposit is another significant factor in liquefaction resistance. This is generally expressed in terms of the initial effective stress prior to the application of any cyclic shear stresses: the greater the initial effective confinement, the greater the liquefaction resistance. The confinement increases with depth because of the geostatic overburden stresses. For situations

"A reduction in soil strength ...can result in the dramatic and dangerous phenomenon called soil liquefaction."

involving level ground, liquefaction is observed most frequently at depths less than six to nine meters.

The initial physical state of the soil is also critical. A reference often used to describe the physical state of granular materials is relative density, a measure of how closely packed the soil grains are with respect to the loosest and the most dense possible conditions. Sands that have relative densities greater than 70 percent of the maximum seldom liquefy, and then only under severe earthquakes.

Several other factors, many of which are difficult to measure quantitatively, contribute to liquefaction resistance. For example, sand layers deposited during the Pleistocene epoch (older than 10,000 years) are much more resistant than more recent Holocene deposits.

Small changes in the particle fabric and weak silaceous cementation may occur as soil deposits age, and may contribute to increased liquefaction resistance.

Old deposits may have been liquefied during prior earthquakes, and in some cases this can increase the resistance to subsequent reliquefaction (although there is evidence that prior earthquakes in an area do not always prevent liquefaction from recurring at the same location).

TYPICAL KINDS OF FAILURE DUE TO LIQUEFACTION

Evidence of soil liquefaction includes not only the failure of many types of structures, but characteristic surface features. Figure 2 shows one of these features: sand boils or sand volcanos, which form when high excess pore water pressures develop beneath an overlying soil layer, and suspensions of water and soil particles are vented upward through cracks or weak zones. These sand boils seldom cause substantial damage and are often useful, since they help indicate the areal extent of liquefaction. They have also been used to date the occurrence of prehistoric earthquakes.

A much more critical form of liquefaction-induced damage is the buoyant rise of buried structures that hold materials lighter than the surrounding soil-water medium. Ordinarily the buoyant forces are resisted by the shearing forces within the overlying soil mass, but if the soil liquefies or loses substantial shearing resistance because of increased pore water pressures, structures such as tanks or large pipelines literally float to the surface (see Figure 3). Failures of this kind can disrupt important lifelines and service utilities, and possibly release toxic substances into the groundwater system.

Extreme building settlements and damage to marine and harbor facilities have also been caused by soil liquefaction (see Figures 4 and 5). Settlement may be caused by shallow liquefaction directly beneath a foundation, or by losses in soil strength caused by the upward flow of water from deeper liquefied-soil zones.

One of the most important areas of concern for geotechnical engineers is the stability of earth dams during earthquakes. The possible consequences were brought dramatically into focus following the 1971 earthquake of magnitude 6.6 in San Fernando, California. As a result of this earthquake, the upstream shell, the dam crest, and a large portion of the downstream slope of the Lower San Fernando Dam failed. Nearly eighty thousand people living downstream were evacuated because of the danger of flooding. The vertical displacement at the top of the dam was as much as nine meters, but

Structural damage caused by liquefaction of soil is illustrated in Figures 3, 4, and 5.

Figure 3. The fuel storage tank at this filling station floated upward due to liquefaction of the surrounding soil during the 1983 Japan Sea earthquake. (Photograph courtesy of M. Kawamura)

Figure 4. Buildings in this apartment complex tilted as much as 60° as a result of soil liquefaction during a 1964 earthquake in Niigata, Japan. High pore water pressures developed beneath the foundation, reducing the supporting capacity of the soil. (Photograph courtesy of G. W. Housner)

Figure 5. Quay walls and bulkhead facilities have often been damaged during earthquakes. This retaining wall has been displaced by a large outward movement into the harbor and by substantial settlement of the ground behind it. (Photograph courtesy of M. Kawamura)

Figure 3

Figure 4

Figure 5

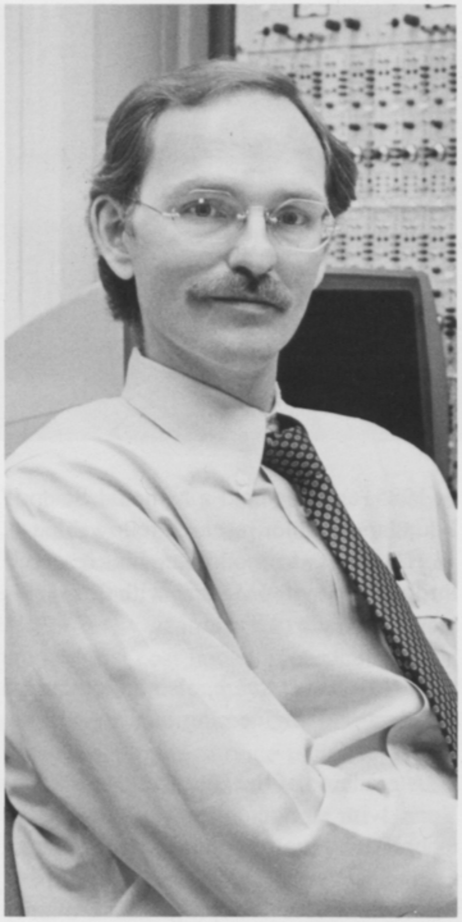
fortunately the water level behind the dam was ten to eleven meters below the crest.

A *flow failure*, as this type is called, is the result of a severe loss of strength because of earthquake loading. All the possible mechanisms for a flow failure relate in some way to either the buildup of large excess water pressures within the soil, or the development of cyclic stresses that exceed the shearing resistance of the foundation material. Presently, there are no completely reliable procedures for predicting the displacements that could occur in large dams containing saturated sands susceptible to flow failure.

THE NEED FOR BASIC RESEARCH IN SOIL DYNAMICS

Prior to 1964, there was little recognition of the importance of soil liquefaction. Since then, much progress has been made in identifying the basic mechanisms involved and in developing methods to minimize liquefaction damage, but there are still several areas in which fundamental research in soil dynamics is needed.

Clean sands, for example, have been studied extensively with respect to liquefaction resistance, but the behavior of nonplastic and plastic silts—among the most common earth construction materials—is less understood. Also, although field experience indicates that gravels and gravelly soils can be susceptible to significant volume changes as well as loss of strength during earthquakes, no reliable methods are available to evaluate the strain potential and liquefaction resistance of such soils. What is needed are reliable methods to identify the situations in which soil failure is likely, and predictive methods to assess the expected ground movements.



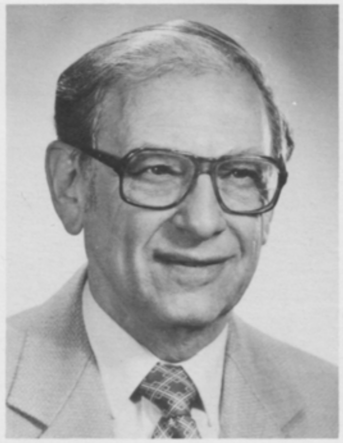
At Cornell this is an active area of research. Our group is working on problems in soil dynamics as part of the program of the National Center for Earthquake Engineering Research, and the current modernization of our geotechnical laboratory will facilitate the effort. Study of the response of soils under earthquake loading will continue to be an important aspect of geotechnical engineering.

Harry E. Stewart is an assistant professor of structural engineering at Cornell. After receiving his Ph.D. at the University of Massachusetts at Amherst in 1982, he served on the teaching and research staffs there and at the University of South Carolina before coming to Cornell .

In addition to soil dynamics, his research areas include railroad track performance, instrumentation, and full-scale field testing. He is a registered professional engineer in New York and South Carolina, and is active as a consultant and on committees of several professional societies.

REGISTER

Carlin



Dalman

■ *Herbert J. Carlin*, the J. Preston Levis Professor of Engineering, is one of five long-time faculty members who became professors, emeritus, this year. He retired in January.

Carlin came to Cornell in 1966 as director of the School of Electrical Engineering, a post he held until 1975.

A specialist in microwave circuits and network theory, he received the Ph.D. from the Polytechnic Institute of Brooklyn, where he later was chairman of the electrophysics department. He holds both B.S. and M.S. degrees from Columbia University.

Carlin has been a visiting professor at institutions in five countries: at the Massachusetts Institute of Technology; the Polytechnic Institutes of both Genoa and Turin, Italy; Tianjin University, China; University College, Dublin, Ireland; and the Technion, Israel. He has held visiting research appointments in France at the Ecole Normale Supérieure in Paris, and at the National Center for Communications in Issy-les-Moulineaux.

He is a fellow of the Institute of Electrical and Electronics Engineers (IEEE), which awarded him the Centennial Medal in 1985, and has held a National Science Foundation senior research fellowship.

He plans to continue his research through a joint program with the Politecnic Institute of Turin.

■ *G. Conrad Dalman,* also a member of the electrical engineering faculty, will retire in July.

A graduate of the City College of New York with a doctorate from the Polytechnic Institute of Brooklyn, he came to Cornell as full professor in 1956 to establish a research program in microwave electronics.

He had spent fourteen years in industry, at RCA, Bell Laboratories, and the Sperry Gyroscope Company. He also taught at the Polytechnic Institute of Brooklyn, which later awarded him its Certificate of Distinction. At Cornell he has served as director of his school and has received its Excellence in Teaching Award.

Since 1980, Dalman has been awarded five United States patents in his specialty fields of microwave and millimeter-wave solid-state devices and circuits. He has served as a consultant to six major industrial firms and has spent leaves at TRW and at Chiao Tung University in Taiwan, where he was manager of the United Nations' China Project. He is a fellow of the IEEE and the American Association for the Advancement of Science.

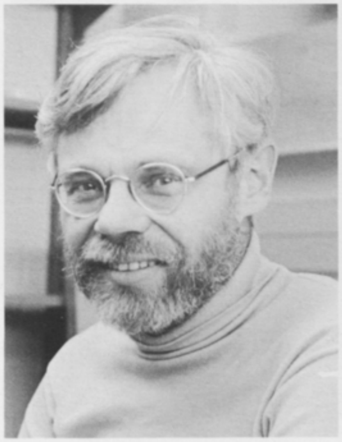
In the near future he plans to complete a textbook on microwave devices and circuits which he started during his last sabbatical leave. He says that he and his wife will remain in Ithaca except for the winter months when they plan to visit children living in California and Virginia.

■ *Arthur F. Kuckes* of the School of Applied and Engineering Physics will become professor, emeritus, in July.

Following undergraduate study at the Massachusetts Institute of Technology, Kuckes spent a year in Göttingen, Germany, as a Fulbright fellow and a year at the University of Paris as a National Science Foundation fellow. After receiving the Ph.D. from Harvard University in 1959, he conducted research in plasma physics at Princeton University and the Culham Laboratory in England. He came to Cornell in 1968.

Since the early 1970s, Kuckes' re-

Kuckes



Slate

Wiegandt

search has been on electromagnetic applications in geophysics; his studies of internal electric currents and conductivity have contributed to an understanding of the geological evolution of the moon and have provided information about the properties of the earth's lower crust.

He has also applied electromagnetic methods of surveying for oil and gas to the control of "blown-out" wells by directional drilling and to problems of petroleum exploration. In 1985 he organized an Ithaca-based firm, Vector Magnetics, that provides service of this kind, and he will continue to work with the company.

■ *Floyd O. Slate*, who will become professor, emeritus, of civil and environmental engineering in July, has been at Cornell since 1949.

After earning B.S., M.S., and Ph.D. degrees at Purdue University, he worked on the Manhattan Project and then taught at Purdue for three years.

A member of the Cornell Department of Structural Engineering, he specializes in the properties and failure of concrete, in microcracking and internal structure of concrete, and in high-strength concrete.

He has served as an industrial consultant in these fields, and in the early 1960s he was a founder of Geotechnics and Resources, Inc., and served as director.

For many years he has worked in the area of low-cost housing, particularly for developing nations; he has researched and implemented programs in seventy countries. His foreign service includes a year (1955–56) as a housing adviser in Pakistan under the sponsorship of the United States Foreign Service. In 1976 he was awarded a senior fellowship by the East-West Center.

Slate has been honored many times by the American Concrete Society: he won the Wason Research Medal three times, received the Anderson Award, and most recently, in 1986, was awarded the Wason medal for the best paper published in the society's journal. At Cornell he received the 1976 Excellence in Engineering Teaching Award.

He is the author of two books and some eighty papers, and he plans to continue to write and publish research papers on concrete. He also plans to travel widely and work internationally on low-cost housing for developing nations.

■ *Herbert Wiegandt* will complete forty years as a Cornell faculty member and become an emeritus professor of chemical engineering in July.

After earning a bachelor's degree and a Ph.D. at Purdue University, Wiegandt worked for six years in research and development at Standard Oil of Indiana and at the Armour Research Foundation. His specialties are the hydraulics of porous moving beds, petroleum processing, and saline-water conversion.

For eleven years, beginning in 1973, Wiegandt spent half of each year in France at the Compagnie Francaise de Raffinage; he retired from the French position in 1982. He has been a Fulbright fellow at the French Petroleum Institute in Paris, and spent subsequent academic leaves there and at the Monsanto chemical company.

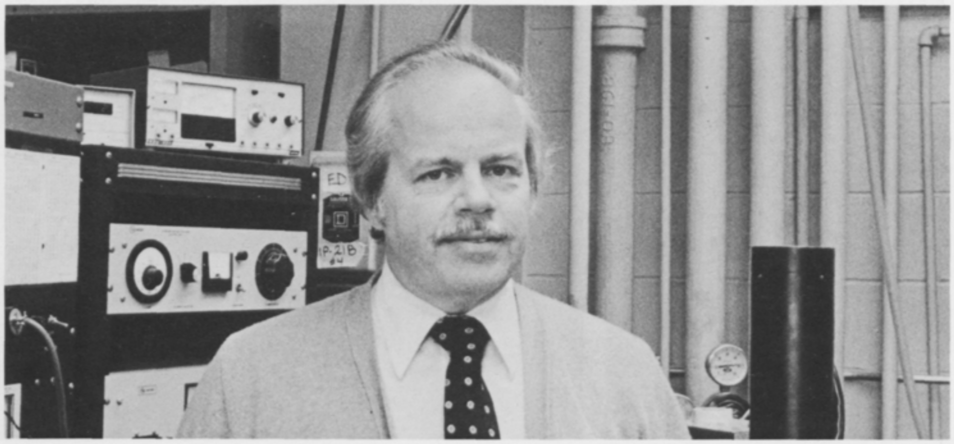
He plans to divide his time principally among Ithaca, Paris, and Geneva. In August he will attend the third World Congress on Desalination in Cannes, France, where he will present a new development in ice crystallization based on the latest research on the Cornell Freezing Process.

■ *Herbert H. Johnson,* professor of materials science and engineering, has been elected to the National Academy of Engineering. He was cited for "pioneering research on hydrogen embrittlement of metallic alloys and for leadership in the management of interdisciplinary materials research."

Election to the academy is generally regarded as the highest professional honor conferred on engineers. Selected this year were eighty-two United States engineers and seven foreign associates.

Johnson earned B.S., M.S., and Ph.D. degrees from the Case Institute of Technology and then taught at Lehigh University before joining the Cornell faculty in 1960. At Cornell he has served as director of the Department of Materials Science and Engineering and as director of the interdisciplinary Materials Science Center. He is a fellow of the American Society for Metals.

Johnson



■ Both a Guggenheim fellowship and the Alexander von Humboldt Foundation's Humboldt Prize were awarded this spring to *Edward J. Kramer,* professor of materials science and engineering. He plans to spend the 1987–88 academic year conducting polymer-diffusion research at the University of Mainz, West Germany, which he described as the "hotbed of polymer science in Europe."

Since joining the Cornell faculty in 1967, Kramer has been a visiting scientist at the Argonne National Laboratory and at institutions in West Germany and Switzerland. He is a fellow of the American Physical Society and received its High Polymer Physics Prize in 1985.

He received his undergraduate education at Cornell and earned the Ph.D. at Carnegie-Mellon University.

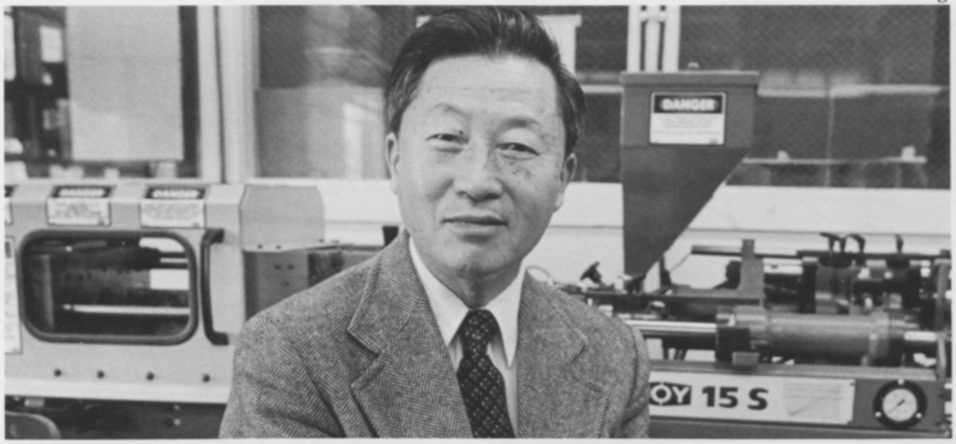
Kramer

■ Also awarded a Guggenheim fellowship this year is *Dennis M. Mills,* staff scientist at the Cornell High Energy Synchrotron Source (CHESS). Mills is believed to be the first non-faculty member at Cornell to have received a Guggenheim. He plans to study new techniques for synchrotron radiation research at CHESS and other sources.

After earning a B.S. degree in physics at Rensselaer Polytechnic Institute, Mills earned the Ph.D. at Cornell in 1979. He has been involved with CHESS since its inception in 1978.

Mills

Wang



Resler

■ *Edwin L. Resler, Jr.*, the Joseph Newton Pew, Jr. Professor of Mechanical and Aerospace Engineering, was recognized this spring by his undergraduate university, Notre Dame, which presented him its College of Engineering Honor Award.

The citation noted his "distinguished achievements in engineering research, teaching, management and service." Specifically mentioned were his leadership as director of the former Graduate School of Aerospace Engineering and as director of the Sibley School of Mechanical and Aerospace Engineering; his service as chairman of the NASA Advisory Committee for Fluid Mechanics; and his fundamental and practical research in high-temperature and chemical kinetic processes, magnetohydrodynamics, ferrohydrodynamics, sonic booms, combustion control, and engine design.

Also cited was his service to his church and community, including work with the Boy Scouts of America, and "the abiding interest and caring he and his wife Frances have developed for handicapped children and the mentally retarded."

Resler received the B.S. degree from Notre Dame in 1947 and the Ph.D. from Cornell in 1951. After a year here as an assistant professor, he taught at the University of Maryland and then rejoined the Cornell faculty in 1956.

■ *Kuo-King Wang*, the Sibley College Professor of Mechanical Engineering, is the recipient of the 1987 Frederick W. Taylor Research Medal awarded by the Society of Manufacturing Engineers.

The citation reads, "His brilliant research, teaching, and writings have perfected a broad spectrum of manufacturing technologies and processes [and] created a superlative record of academic and engineering achievements, benefitting manufacturing worldwide."

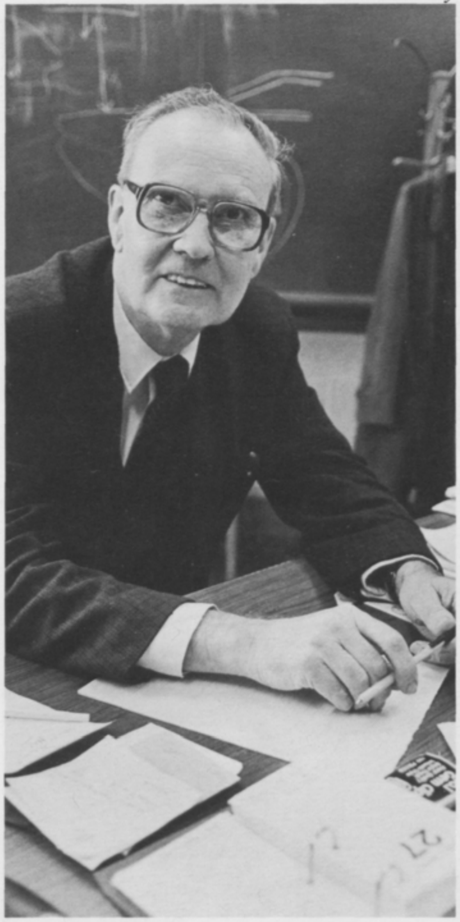
Wang, a specialist in manufacturing processes, numerical control, computer-aided design and manufacturing, and polymer processing, is the director of the Cornell Injection Molding Program and co-founder of the university's Manufacturing Engineering and Productivity Program.

He holds a baccalaureate degree from the National Central University in China, and M.S. and Ph.D. degrees from the University of Wisconsin at Madison. Before joining the Cornell faculty in 1970, he had seventeen years of industrial experience in China, Japan, Germany, and the United States and taught at the University of Wisconsin.

Included among his honors are the ASME Blackall Machine Tool and Gage Award, the Adams Memorial Membership Award of the American Welding Society, and a TRW fellowship in manufacturing engineering.

He is a fellow of ASME and an active member of the International Institution for Production Engineering Research.

Conway



■ *John W. Wells,* emeritus professor of geological sciences since 1973, has been awarded the James Hall Medal by the New York State Geological Survey. The medal will be presented at a fall meeting of the state Geological Association.

A paleontologist who specializes in fossil corals, Wells carries on an active research program from his home office in Ithaca.

He did his graduate work at Cornell, earning the M.A. in 1930 and the Ph.D. in 1933. He joined the geology faculty in 1948 and was chairman from 1962 to 1965. He is a member of the National Academy of Sciences.

■ *Jack E. Oliver,* the Irving Porter Church Professor of Engineering, has been elected president of the Geological Society of America.

The society, which will celebrate its centennial in 1888, was formed at a meeting of geologists and paleontologists held at Cornell. Oliver is the first Cornell professor to serve as president since Heinrich Ries held the post in 1929.

Oliver, a specialist in the structure and evolution of continents, came to Cornell in 1971 as chairman of the Department of Geological Sciences. Previously he was on the faculty at Columbia University, where he received his doctorate and was associated with the Lamont-Doherty Geological Observatory.

Currently he is director of the Cornell-based Institute for the Study of the Continents, and of an associated program for industrial affiliates. He was a founder of the federally funded Consortium for Continental Reflection Profiling, which is mapping the deep structure of the earth's crust in parts of the United States.

■ *Harry D. Conway* rounded out his fortieth year on the Cornell engineering faculty by accepting the college's 1987 Excellence in Teaching Award at a presentation April 30 during the annual Engineering Conference on campus.

The award, which carries a $1,500 prize, is sponsored by the Cornell Society of Engineers (the alumni association of the College of Engineering) and the student honorary society Tau Beta Pi. The recipient is chosen on the basis of student nominations.

Conway, a professor of theoretical and applied mechanics, is a specialist in structural mechanics and lubrication. He holds the degrees of B.Sc., Ph.D., and D.Sc. from the University of London, and the M.A. and Sc.D. from Cambridge University.

He came to Cornell in 1947 from Cambridge University, where he was assistant director of studies at St. Catharine's College.

His previous honors include a Guggenheim fellowship and a National Science Foundation senior postdoctoral fellowship. Both leaves were spent at Imperial College, London.

■ *John E. Hopcroft,* the Joseph C. Ford Professor of Computer Science, was elected this spring as a fellow of the American Association for the Advancement of Science.

He is a specialist in theoretical computer science, and has published extensively in the fields of algorithms and data structures. He has been on the Cornell faculty since 1967.

Hopcroft is a fellow of the Institute of Electrical and Electronic Engineers. Last year he received the Turing Award of the Association for Computing Machinery.

Raymond G. Thorpe is the only Cornell professor to have been chosen in all four years of the Presidential Scholar program. The student is Goeffrey C. Achilles.

■ Both students and the teachers they name as the most influential in their undergraduate careers are honored in the annual selection of Presidential Scholars at Cornell. This year six engineering students were among the thirty-four scholars nominated by their deans and recognized by President Frank H. T. Rhodes at a luncheon ceremony in May.

Goeffrey C. Achilles named *Raymond G. Thorpe*, professor of chemical engineering. *Peter E. DelVecchio* named *John Belina*, assistant dean who also teaches electrical engineering. *Mark D. Doyle* named *Mark S. Nelkin,* professor of applied and engineering physics. *Walter H. Hartung* named *Hasan S. Padamsee*, senior research associate in nuclear studies. *Terry J. Linsey* named *James S. Thorp,* professor of electrical engineering. *Susan M. Lord* named *Michael O. Thompson,* assistant professor of materials science and engineering.

■ The 1987 Dean's Prizes for Innovative Teaching have been awarded to five College of Engineering professors, it was announced by Dean William B. Streett.

One of the three $1,500 prizes went to *John F. Abel* of the Department of Structural Engineering; one was shared by *Dieter G. Ast* and *David T. Grubb* of the Department of Materials Science and Engineering; and the third was shared by *Peter L. Jackson* and *John A. Muckstadt* of the School of Operations Research and Industrial Engineering.

The prizes were awarded April 30 during the college's fourth annual Engineering Conference for alumni.

Abel's award was for the planning, design, and development of graphical instructional programs for several structural engineering courses.

Ast and Grubb were recognized for establishing the Computer Simulation Facility used for courses in materials science and engineering, and for developing needed software.

Jackson and Muckstadt won their prize for contributions to undergraduate teaching, including the development of a computer laboratory.

■ The annual selection of outstanding faculty members, teaching assistants, and students has been reported by several schools and departments.

In the Department of Agricultural Engineering, *Stephen P. Etheridge,* a visiting professor, was chosen by the student organization for the Outstanding Faculty Award, which was presented at the annual banquet of the student branch of the American Society of Agricultural Engineers. This award recognizes contributions to both the profession and the academic program. *Roelof de Vries* was selected as the outstanding graduate teaching assistant and honored at a College of Agriculture and Life Sciences luncheon.

Winners of the Trevor R. Cuykendall Memorial Awards were announced by the School of Applied and Engineering Physics. *Mark David Doyle* was chosen as the outstanding senior, and *Russell F. Loane* as the most outstanding teaching assistant. They will each receive a cash award and a certificate, and their names will be added to plaques in the school lounge. These awards are funded through gifts from alumni and friends and are in honor of the late Professor Cuykendall.

This year's outstanding teaching assistants in the School of Chemical Engineering are *J. Kent Carpenter* and *Cynthia D. Holcomb.* Undergraduates who received honors include *Geoffrey C. Achilles,* the American Institute of Chemists award; *Randall W. Verhoef,* the American Institute of Chemical Engineers prize; *Matthew M. Walsh,* the Dow award for the outstanding junior; *John J. Schleuter,* the Procter and Gamble award for technical excellence; and *Christopher J. Harris,* the Twin Tiers American Institute of Chemical Engineers award for the outstanding scholar.

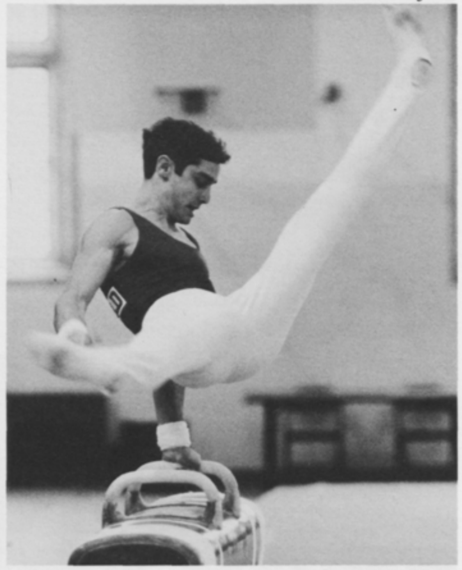
Richard N. White was named 1987 Professor of the Year in the School of Civil and Environmental Engineering. Chi Epsilon announced the selection at the commencement reception. Also recognized were *Stephen Paul Pessiki,* winner of the $500 John E. Perry Teaching Assistant Prize, and three senior winners: *Christopher R. Tull,* the $500 John E. Perry Undergraduate Prize; *Matthew A. McHugh,* the Moles Student Award; and *Phaik Choo Phuah,* the gold Fuertes Undergraduate Medal. Earlier in the spring seniors *Nicos Y. Constantinides* and *Christopher R. Tull* received the American Society of Civil Engineers awards for merit and service, respectively, and graduate student *Jerome F. Hajjar* received the $1,000 George Winter Fellowship.

Undergraduates in the School of Operations Research and Industrial Engineering chose *Peter Jackson* as this year's most outstanding professor, and *Todd Whitlow* as the most outstanding teaching assistant. Ballots were distributed and tabulated by the student chapter of the Institute of Industrial Engineers. The faculty selected *Jennifer Black* as the most outstanding senior, and *C. J. Glynn* as the most outstanding student in the Master of Engineering program.

■ Three engineering students who won special athletic honors this year are *John Bajusz,* a senior in operations research and industrial engineering; *John Bayne,* a junior in mechanical engineering; and *Bruce Sonnenfeld,* a senior in electrical engineering.

Bajusz was named to the All-Ivy first team in basketball for the third year in a row; as a freshman he won honorable mention and was rookie of the year. He is enrolled in the six-year program in

Sonnenfeld



engineering and business administration, and will be at Cornell next year as a graduate student.

Bayne was named to the first team of the Adidas Scholar-Athlete Soccer All-American Team for the second year in a row. The team is selected by the Intercollegiate Soccer Association of America on the basis of both academic and athletic achievement. A midfielder, he finished the 1986 season as the most prolific scorer both on the team and in the Ivy League, and he also won first-team All-Ivy honors. In addition to playing soccer, he is a sprinter on the Cornell track team. His grade-point average for the past five terms was 4.18 (higher than an A).

Sonnenfeld, a record holder in several gymnastics events, was chosen all-around champion by both the North American Gymnastics League and the Ivy League. He is the first Cornellian ever to win both titles. Sonnenfeld will enter the Cornell Master of Engineering program next fall and will serve as assistant coach.

Watching the Plans Take Shape

■ A new building to house two engineering departments and Cornell's supercomputer center will be built near Grumman Hall, it was announced by William B. Streett, dean of the College of Engineering. The design concept has been approved and construction is expected to begin this fall.

These developments are the first of a proposed major building and renovation project for the engineering campus, Streett said. The Master Plan calls for construction that would increase by 50 percent the floor space in buildings on the college campus.

The supercomputer center, which is officially the Center for Theory and Simulation in Science and Engineering, is a national facility located at Cornell. The building in which it is to be housed is included in the Master Plan because the center is integrated functionally with the College of Engineering, Streett said. More than half the Cornell faculty members working in the center are from the college.

The proposed eight-story building will be one of the largest at Cornell. The $22–$25 million cost will be met partly by a New York State grant and loan totalling $10 million.

The architectural firm of Gwathmey Siegel & Associates of New York City is designing the building and also proposing a concept for the overall Master Plan. In general, the proposal is to construct new buildings around the periphery of the existing complex.

The next construction is expected to be an enlarged facility for the School of Electrical Engineering. This is likely to be an L-shaped building that would incorporate two wings of the present Phillips Hall.

Right: Two views of the architects' model of the proposed new building.

The top view is from the northeast. Cascadilla Gorge is to the left and the main section of the building is on the present Grumman Hall parking lot. Grumman Hall is behind the new building and Upson Hall is to the right.

The bottom view is from the southwest, looking toward Hoy Field and the football stadium. The adjacent building (at left) is Grumman Hall.

■ A large construction project that has had little effect on the appearance of the campus is a two-story addition to Upson Hall. Designed by Perkins and Will, the building's original architects, the extension adds to the height of the structure but is similar in exterior design.

The addition has added 36,000 square feet of space. The project also included renovation of 4,800 square feet of space in the original building.

The new quarters, dedicated April 30, are occuped mainly by the Department of Computer Science. Included are offices, conference and seminar rooms, laboratories, a library, and a lounge.

■ The National Research and Resource Facility for Submicron Structures (NRRFSS) has been awarded a five-year, $10 million project-renewal grant from the National Science Foundation and will change its name to reflect a new research focus. Beginning the first of October, the laboratory will become the National Nanofabrication Facility (NNF).

According to Gregory Galvin, deputy director, Cornell has been a leader in submicron technology since the founding of NRRFSS in 1977, and the new concentration on nanometer-scale devices should enable the university to stay ahead. The facility's director is Edward D. Wolf, who has been on sabbatical leave this year.

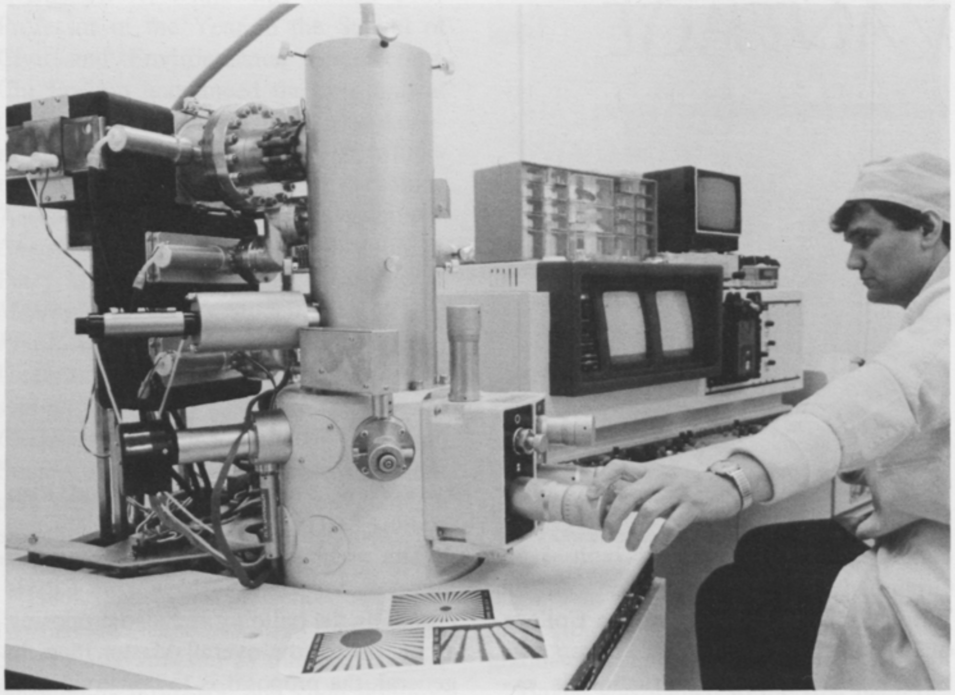
A micron is 10^{-6} meter and a nanometer is 10^{-9} meter. The devices now being worked on are in the range of 25 nanometers, about ten times smaller than those previously studied. "Until now," Galvin said, "we have concentrated on building devices down to approximately one-quarter of a micron, about two hundred times smaller than the diameter of a human hair. But now there are several labs around the country capable of making such devices, so it's time for us to set our sights 'lower'. We will be building devices with dimensions in the 25-nanometer range, around two thousand times smaller than a human hair."

Current projects include studying how blood cells squeeze through small openings in bone marrow; developing improved ways to sculpt tiny lasers for optical communications systems; building microscopic terrains to study plant fungi; and creating superfast transistors.

The work is done with the facility's thirty machines, housed in the "clean room" environment of Knight Laboratory. The building is named for Lester B. Knight, a Cornell benefactor who is chairman of an architectural engineering firm.

NRRFSS is available to visiting scientists from other universities, government, and industry—the only laboratory of its kind in this country. This spring scientists from thirty-three universities and corporations were conducting research at the facility.

The NSF grant will support approximately half the facility's operating expenses for the next five years. A contingency for $2 million of the total grant is that $5 million be provided by industry or New York State. The facility also receives support from the university.



New equipment that will enable researchers at the National Nanofabrication Facility to work at smaller dimensions includes this Hitachi S-800 scanning electron microscope. It is capable of very-high-resolution (2-nanometer) imaging.

Other new equipment includes an electron-beam lithography system usable in the nanometer range.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the four-month period August through November, 1986. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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