Earthquake Engineering Research, 1982 (1982)

Pages
278

Size
5 x 8

ISBN
0309328187

Committee on Earthquake Engineering Research;
National Research Council

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the federal government. The Council operates in accordance with general policies determined by the Academy under the authority of its congressional charter of 1863, which establishes the Academy as a private, nonprofit, self-governing membership corporation. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

This study was supported by the National Science Foundation under Contract No. CEE-8111095. The opinions, findings, and conclusions or recommendations are those of the Committee and do not necessarily reflect the views of the National Science Foundation.

Copies of this report may be obtained from:

National Technical Information Service
Attention: Document Sales
5285 Port Royal Road
Springfield, Virginia 22161

Report No. CETS-CEER-001B
Price codes: Paper A13, mf A01

A limited number of free copies of this report are available on request to:

Committee on Earthquake Engineering Research
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Committee on Earthquake Engineering Research

Chairman

GEORGE W. HOUSNER, California Institute of Technology, Pasadena

Members

MIHRAN S. AGBABIAN, Agbabian Associates, El Segundo, California

CHRISTOPHER ARNOLD, Building Systems Development, Inc., San Mateo, California

RAY W. CLOUGH, University of California, Berkeley

LLOYD S. CLUFF, Woodward Clyde Consultants, San Francisco, California

WILLIAM J. HALL, University of Illinois at Urbana-Champaign

ROBERT D. HANSON, University of Michigan, Ann Arbor

DONALD E. HUDSON, University of Southern California, Los Angeles

JOSEPH PENZIEN, University of California, Berkeley

RALPH H. TURNER, University of California, Los Angeles

ANESTIS S. VELETSOS, Rice University, Houston, Texas

ROBERT V. WHITMAN, Massachusetts Institute of Technology, Cambridge

Staff

O. ALLEN ISRAELSEN, Project Manager
LALLY ANNE ANDERSON, Administrative Secretary
JOANN CURRY, Secretary
STEVE OLSON, Consultant Editor

Contents

Preface

Construction in the United States presently represents an investment of approximately $230 billion per year. Of this amount, approximately $180 billion per year is invested in the some 40 states that have experienced moderate or major earthquakes in the past. (The only states that have not experienced widely perceptible earthquake shaking during historical times are Wisconsin, Iowa, and North Dakota. Minnesota, Michigan, Mississippi, Louisiana, and Florida have not experienced moderate to strong shaking.) In view of the potential loss of life and possibly great economic losses that large earthquakes could cause, it is important that the United States make substantial efforts to mitigate the hazards of earthquakes by developing safe and economical methods of earthquake-resistant design and construction.

In 1967-1968 the Committee on Earthquake Engineering Research of the National Research Council-National Academy of Engineering prepared a report that discussed the practical problems related to earthquakes and the research needed to solve these problems.* The purpose of the report was threefold:

1. To describe briefly the nature of the earthquake problem and the present state of knowledge in the field.
2. To indicate to research workers where knowledge was lacking and where further research was needed.
3. To bring the earthquake problem to the attention of government agencies and other organizations that initiated, directed, or funded research and to provide them with information helpful in planning.

The report was influential in calling attention to the earthquake problem, in shaping legislation, and in guiding the formulation of a comprehensive program of research aimed at solving major problems of safety and economy posed by earthquakes.

During the 1970s a number of damaging earthquakes occurred in the United States. The greatest loss was suffered in the 1971 San Fernando, California, shock, which caused more than $1 billion in damage.

---

*Committee on Earthquake Engineering Research, *Earthquake Engineering Research*, National Academy of Sciences, Washington, D.C., 1969.

Substantial research programs on earthquake hazard mitigation were subsequently developed in earthquake engineering and geophysics by the National Science Foundation (NSF), in seismology and geology by the U.S. Geological Survey (USGS), in building standards by the National Bureau of Standards, in seismic analysis of nuclear power plants by the Nuclear Regulatory Commission, and in disaster relief by the Federal Emergency Management Agency. The total federal support for these programs was approximately $60 million in fiscal year 1981. The 1969 *Earthquake Engineering Research* report and a subsequent report* provided important guidance for the researchers and managers of these programs.

In 1981 the National Science Foundation requested that the National Research Council make another study of earthquake engineering research to evaluate progress since 1968 and recommend research opportunities for the next 10 years. The study's purpose was to enhance the engineering aspects of efforts in earthquake hazard mitigation now under way in the United States.

The National Research Council organized a committee specifically for this purpose. It included specialists in earthquake engineering, soil and rock mechanics, structural dynamics, structural design, architecture, the design of lifeline facilities (transportation, power, communications, water, sewer), disaster research, and coastal engineering. Additional specialists were asked to serve on relevant working groups appointed for the study. (See Appendixes A and B for biographical sketches of committee members and a listing of working group members.)

In preparing this report, the Committee addressed the following two questions: What progress has research produced in earthquake engineering, and which elements of the problem should future earthquake engineering research pursue? So many advances have occurred in earthquake engineering since 1968 that the Committee could not identify and discuss all of them in a relatively short report. Thus this report is not complete in that sense, but it does include sufficient coverage to make clear that very significant progress has indeed been made.

During the course of its deliberations, the Committee identified areas in which research programs could make significant advances. While the report was being prepared, several committee members also visited Japan and China to learn about their earthquake engineering research efforts. The committee members found that both countries are expending greater research efforts than is the United States, particularly in experimental research. Clearly, these two countries are rapidly

---

*National Science Foundation and Department of Interior, *Earthquake Prediction and Hazard Mitigation Option for USGS and NSF Programs*, U.S. Government Printing Office, Washington, D.C., September 1976.

1

Overview and Recommendations

In this report, earthquake engineering is broadly interpreted as encompassing the practical efforts to mitigate earthquake hazards. Research in earthquake engineering thus consists of the investigation and solution of problems posed by destructive earthquakes. These problems may include the assessment of earthquake hazards, the nature and characteristics of destructive ground motions, the performance of structures during earthquakes, the earthquake-resistant design of structures and facilities, and the protection of the public. This report seeks to evaluate the effectiveness of past earthquake engineering research by assessing the influence this research has had on the practice of engineering, the mitigation of damage, and public safety and welfare during future earthquakes. In addition, this report identifies areas of research that should be given special consideration in future research programs. During the preparation of this report, it became increasingly evident that the earthquake problem in the United States is much broader than has usually been considered in the past. All facets of our modern industrialized society can be severely affected by earthquakes, and if the earthquake problem is to be solved all of its aspects must be considered.

The results of earthquake engineering research form the basis for the safer design of many kinds of buildings, emergency, essential, and critical facilities, commercial, financial, and industrial facilities, government facilities and operations, and other structures and systems. Each such category requires different kinds of information and different methods of coping with the hazard. For example, in the design of ordinary buildings economic considerations are relatively important, whereas for emergency facilities such as fire and police stations, hospitals, and emergency operation centers the critical element is that they continue to function immediately after an earthquake. The main consideration for essential facilities or lifelines—which include water and sewage systems; gas, electricity, and fuel distribution systems; and communications systems—is that the system may be restored to operation without serious impact on the public. For such critical facilities as major dams, nuclear power plants, petroleum facilities, offshore platforms, liquefied natural gas (LNG) storage tanks, and chemical and biological facilities, the consequences of uncontrolled failure are so serious that safety is an overriding consideration. Commercial, financial, and industrial facilities are key elements in large urban areas and must be protected from severe, prolonged disruption. Government facilities and operations, which include military airports, naval installations, army facilities, and government communications systems, must be protected from serious damage or prolonged disruption of operations.

Earthquake engineering is a relatively new field. Fifty years ago building codes included no earthquake requirements, there were no recordings of strong ground shaking, the education of engineering students did not include any information on the effects of earthquakes on structures, and knowledge of earthquake engineering was virtually nonexistent. In his paper on building damage in the 1906 San Francisco earthquake, which appeared in the 1907 *Transactions of the American Society of Civil Engineers*, Professor Charles Derleth, Jr., stated, "An attempt to calculate earthquake stress is futile. Such calculations could lead to no practical conclusions of value." This remained the general view until the destructive Long Beach, California, earthquake of March 10, 1933. In fact, the field of earthquake engineering in the United States can be said to have been born at 5:54 p.m. on that date, when this magnitude 6.2 earthquake killed several hundred persons, caused some $600 million in damage (1982 dollars), and forcibly brought the problem to the attention of legislators and public officials.

Following the Long Beach earthquake, west coast universities carried out some research projects, but these were interrupted by the second world war and not begun again until the 1950s. Only when the National Science Foundation began funding research did an effective program of earthquake engineering research come into being.

The effectiveness of earthquake engineering research can be attributed, in large part, to the fact that so little was known about the subject. Almost every incremental increase of knowledge satisfied a definite practical need. Also, the planning, design, and construction of major projects, such as nuclear power plants, high-rise buildings, offshore platforms, dams, LNG storage tanks, and oil pipelines, have created special needs for information on earthquake engineering, and these needs have tended to outpace research.

The research considered in this report is mainly basic earthquake engineering research, which aims to develop relevant information about the occurrence and generation of destructive earthquakes, about the nature of ground motions, about the behavior of man-made structures during earthquakes, about methods of analyzing the performance of structures during earthquakes, about the dynamic properties of materials and structural elements, about the dynamics of soils and soil structures, and about urban safety and welfare. Engineering

The magnitude 6.3 earthquake of March 10, 1933, in Long Beach, California, damaged many school buildings, such as the high school shown here. It occurred late on a Friday afternoon when no students were in the schools, though some 200 people were killed in other buildings. This earthquake marked the beginning of earthquake engineering in the United States.

organizations and government agencies in turn use this information to develop better methods of seismic engineering and earthquake protection.

When assessing the effectiveness of earthquake engineering research, two different approaches might be employed. One would be to review research reports and published papers and subjectively judge which have contributed valuably to knowledge in earthquake engineering; however, this report does not employ this method. Rather, this report identifies improvements that have actually taken place in coping with earthquakes. This has the advantage of being an objective assessment, though it may overlook valuable research that has not yet worked down to the level of practical application.

This introductory chapter summarizes some of the material covered in later chapters and presents the more important recommendations made in those chapters.

The Earthquake Problem

One way of describing the earthquake problem is to say that earthquake engineering research seeks to mitigate future disasters by reducing loss of life, economic losses, the adverse impacts on society, and the impacts on governmental and military operations. The possibility of future disaster provides strong motivation for addressing the earthquake problem; in this, it differs from most other engineering research, which aims at providing social benefits but does not so clearly seek to prevent a major disaster.

Three physical conditions determine the occurrence of an earthquake disaster. First is the magnitude of the earthquake, because a small earthquake will not have sufficiently severe ground shaking to produce extensive damage. In fact, in the highly seismic regions of the United States an earthquake having a Richter magnitude greater than 5.5 is needed to produce significant damage. Second, the source of the earthquake must be sufficiently close to a city, because at greater distances the ground shaking will be attenuated below the level of serious damage. Third, the possiblity of disaster depends on the degree of earthquake preparedness. A city with poor preparation will suffer much more than a city with good preparation. Obviously, the larger and nearer the earthquake and the poorer the preparation, the greater will be the disaster.

The Sylmar Veterans Administration Hospital collapsed during the 1971 San Fernando, California, earthquake. Forty-nine people were killed in the collapse, and 16 survivors were dug out of the ruins. This photograph was taken 2-1/2 days after the earthquake, just before the last survivor was found.

An example of an extreme earthquake disaster is the one that shattered the city of Tangshan, China on July 28, 1976. This industrialized city of approximately one million people is located 100 km (60 miles) east of Beijing. The Chinese building code had placed Tangshan in a seismic zone for which earthquake-resistant design was not required, so this city of unreinforced brick buildings was almost totally unprepared. The magnitude 7.8 earthquake was a large event generated by a fault slip over a length of some 140 km. The epicenter of the earthquake was within the city and the fault slip extended beyond both of its borders. Thus this very large earthquake occurred very close to a very poorly prepared city, and the result was a very great disaster. Eighty-five percent of the city's buildings collapsed or were severely damaged, and several hundred thousand people lost their lives.* Industries in Tangshan, including steel plants, cement plants, locomotive works, and coal mines, were put out of operation for extended periods of time, and by 1982 only one half of the city had been rebuilt.

Such an earthquake disaster, causing the deaths of perhaps one third of a city's inhabitants, is not unprecedented. A similar disaster, though on a smaller scale, struck the unprepared city of Agadir, Morocco (population 30,000), on February 29, 1960, when a magnitude 5.7 earthquake centered beneath the town killed 10,000. Fortunately, a majority of the world's earthquakes do not occur close to a city and, though causing some damage and deaths, do not cause a disaster. Nevertheless, the possiblity that a future earthquake will occur close to a city provides strong motivation for earthquake engineering research. Large but infrequent earthquakes have occurred in the midwestern and eastern parts of the United States (in New Madrid, Missouri, in 1811-1812 and in Charleston, South Carolina, in 1886), and since cities in these regions are poorly prepared there exists the potential for greater disaster in those parts of the country than in the western United States where cities are better prepared.

Although in theory it might be possible to construct a completely prepared city that could survive the strongest shaking without damage, it would not be practicable to do so, even if all the necessary information were available. For example, nuclear power plants are designed to withstand the maximum expected ground shaking, and this requires a large and sophisticated engineering effort that must make conservative judgments, producing relatively costly structures and facilities. If all the structures in a city were researched and analyzed as thoroughly and designed as conservatively, there would not be enough engineers

---

*Official statistics have never been announced, but Chinese engineers speak of 250,000 deaths, presumably a lower bound. Other estimates have placed the number of casualties at 400,000 to 500,000.

to carry out the required effort and construction costs would severely curtail the number of structures that could be built. It is therefore necessary to take a different view of the earthquake problem. The design of a structure should be based on considerations of the degree of seismic hazard, the consequences of damage, and the overall cost. Because larger earthquakes occur less frequently than smaller earthquakes, and because the area affected by strong shaking in any earthquake is less than the area affected by moderate or weaker shaking, the probability that a structure will experience very strong ground shaking during its lifetime is relatively small compared to the probability of its experiencing moderately strong ground shaking. Economic considerations then indicate that there is "acceptable damage" whose cost of repair in the long term is less than the cost of building to prevent this damage.

The concept of acceptable damage involves monetary loss, but loss of life is, in general, not acceptable. A broad consideration would indicate that for a city acceptable damage should occur infrequently and should not have an unduly severe impact on the population. National considerations would indicate that acceptable damage should not have a severe impact on important governmental services, military installations, etc. There is a need for research to determine what is acceptable damage and how to design to achieve it.

Application of Results From Earthquake Engineering Research

In a broad sense the results of earthquake engineering research are applied to protect life and property and to reduce adverse impacts on society. Thus the users of the results of earthquake engineering research are all the individuals and groups in our industrialized society that could be adversely affected by an earthquake and therefore must consider earthquake protection or earthquake disaster mitigation. The ultimate beneficiaries of earthquake engineering research are the citizens of the country, but the immediate users of the research results are the various professions, industries, and government agencies that are concerned about earthquake hazards.

Earthquake engineering research can be divided into two categories:

1. Applied research for immediate practical application. For example, can the electrical switching gear for a nuclear power plant survive strong ground shaking? This question is answered through applied research done by or for the equipment manufacturer; this report does not consider such research.

2. The more basic research that provides the knowledge and data needed to do the applied research or develop methods of design.

The results of basic earthquake engineering research ultimately find use in practical applications, though considerable time may elapse before the results are used fully. The way in which this research usually leads to practical application is as follows: the owners, planners, and designers of special facilities, such as nuclear power plants, major dams, offshore drilling platforms, and high-rise buildings of fifty stories or more, usually recognize the advantages to be gained by making use of research results. They gather these results by reviewing technical publications and interacting with research workers. After critical facilities and high-technology projects have used these results, the state of the art works its way down to the design of ordinary engineered structures and facilities that are governed by building codes, industrial codes, and other standards. Finally, nonengineered structures, such as single-family dwellings, are affected through highly simplified requirements in building codes, which the builder follows without necessarily understanding why they are required.

The lag time for research results to be used in critical facilities is, typically, about one to three years. For research to be reflected in building codes and other codes usually takes on the order of five to ten years or longer. For nonengineered structures the lag time may be much longer.

Following are some examples of the application of results from earthquake engineering research to special facilities.

High-Rise Buildings

Very tall high-rise buildings are densely populated, with as many as 10,000 people in a single building, and represent major investments of as much as $200 million each. The owners thus usually require that the methods of earthquake analysis and design used for them be based on the latest relevant research results. When designing high-rise buildings of 40 to 60 stories in Los Angeles, for example, seismic hazard assessments have estimated the nature and intensity of ground shaking that regional earthquake faults could produce, and dynamic analyses with digital computers have determined how the structures would vibrate in response to the ground shaking. The buildings were then designed so that the structural members could accommodate the stresses and strains. Similar seismic designs have been made in other cities. Such structures can be said to have, in effect, successfully experienced several strong earthquakes prior to construction. These procedures for the seismic design of high-rise buildings have gone beyond the building code requirements and were developed through interaction with research workers.

Major Dams

The disastrous consequences of failure require that a major dam receive careful seismic analysis and design. For example, the dams of the $5 billion California State Water Project, which brings water from the Feather River to southern California, are sited in highly seismic regions, and these have undergone advanced earthquake analysis and design based on the results of research. The California State Department of Water Resources has had an Advisory Committee for Earthquake Analysis, which is composed mainly of university research workers, for the past 15 years, and this group brought the latest research results to the attention of the dams' designers. The Bureau of Reclamation, the U.S. Army Corps of Engineers, and other organizations make similar use of earthquake engineering research in the design of dams in many parts of the country. These design procedures are also being adopted in other parts of the world. This would not have been possible without the information developed by earthquake engineering research.

A separate problem is posed by the over 1,000 existing dams in California, most of which were constructed before the development of earthquake engineering, whose resistance to earthquakes is not known. The California State Division of Dam Safety is now carrying out a program to evaluate their safety using dynamic seismic analyses and relevant research results. There are, of course, many dams in other seismic regions of the United States, and these pose a special problem to state governments.

Electric Power Facilities

Electric power companies in seismic regions are using the results of earthquake engineering research to improve the earthquake resistance of their generating and transmission systems and to develop earthquake design criteria for equipment that they purchase. The 1971 San Fernando earthquake heavily damaged electric power facilities, forcibly indicating the need for improved methods of seismic design.

Nuclear Power Plants

Because safety is an overriding concern in the design of nuclear power plants, great attention is focused on assessing the seismic hazard and designing the structures and associated facilities and equipment to resist the maximum expected ground shaking. The methods of analysis employed and the seismic resistances of the end products go far beyond the requirements of the building code. Nuclear power plants anywhere in the United States are subjected to very advanced methods of earthquake analysis and design to ensure their safety, even if the probability of shaking is very small.

The rapid development of the nuclear power industry generated an

This electrical power equipment collapsed during the San Fernando earthquake of 1971. Using research results, improved methods of seismic analysis and design have been developed for electrical equipment that should prevent such disastrous damage from future strong ground shaking. Because such equipment is built of special materials and must satisfy special electrical requirements, optimum methods of seismic design are very difficult to develop.

urgent need for advanced earthquake engineering information. Without the earthquake engineering research carried on in the United States over the past several decades, the modern seismic design of nuclear power plants would not be possible today. In fact, the earthquake design of nuclear power plants throughout the world is based to a large degree on research performed in the United States

LNG Facilities

Liquefied natural gas storage tanks and associated facilities in seismic regions are analyzed and designed by advanced methods that use the latest results of earthquake engineering research. These facilities pose special problems of engineering analysis and design, as well as of safety, that are not encountered in the design of other structures. These analyses and designs would not be possible without the results of earthquake engineering research.

Offshore Drilling Platforms

Large offshore drilling platforms, such as the 900-ft Hondo platform off the coast of Santa Barbara, California, represent investments of

$100 million or more each and pose potential environmental hazards. For these reasons they undergo advanced methods of earthquake analysis and design that are based on the latest results of earthquake engineering research and interactions with research workers. U.S. companies use the same methods of design for offshore platforms in seismic regions in other parts of the world.

Oil and Gas Pipelines

The designs of the Alaska oil pipeline and the Alaska-U.S. gas pipeline incorporate the results of earthquake engineering research. These facilities, because of their unusual dimensions and potential for environmental impact, also pose special seismic problems whose solutions require a broad knowledge of earthquake dynamics and structural behavior.

Bridges

During the past decade important advances have been made in the seismic design of bridges. Earthquake damage to bridges in the United States and in many foreign countries has emphasized the need for improved seismic design, and the results of research have been applied to achieve this. There has been a corresponding upgrading in the seismic design requirements of the *Seismic Design Guidelines for Highway Bridges* of the American Association of State Highway and Transportation Officials.

High-Technology Operations

High-technology organizations, those that have a high level of scientific and technical expertise, have applied the results of earthquake engineering research to their operations. When an earthquake problem is encountered, these companies can direct highly qualified persons to work on its solution. These persons speak directly with research workers to learn the latest research results and then translate them into a form suitable for their design engineers. Selected examples of companies that are doing this follow.

1. IBM manufacturing facilities in California produce highly specialized electronic computer components. Several years ago IBM recognized that a strong earthquake might damage these facilities, which could consequently disrupt their computer manufacturing. After an exchange with research workers, a program was set up to analyze and strengthen equipment and buildings to forestall disastrous earthquake damage.
2. AT&T, aware that earthquakes can put communications systems out of operation just when relief operations require the ability to

communicate quickly, has for a number of years had an earthquake group studying the application of research results to protect its operations throughout the United States. Their facilities have performed above average in recent earthquakes.

3. Companies such as General Electric provide mechanical and electrical equipment for nuclear power plants, and this must be highly resistant to earthquakes. The results of earthquake engineering research have been used to design and test this equipment. Of course, all other companies that supply critical equipment for nuclear power plants must perform similar design and testing. If they do not have in-house expertise, they hire outside consultant organizations to extract the necessary information from available research results. An example of such an organization is the Southwest Research Institute, which developed a shaking table for seismic testing of special equipment.

4. The Lockheed Aircraft Company, which has an assembly plant in Palmdale, California, close to the San Andreas Fault, became concerned about a repetition of the 1857 magnitude 8.3 Fort Tejon earthquake on this segment of the fault. Of particular concern was the possibility that newly assembled planes awaiting delivery would be damaged. With advice from research workers, vibration analyses were made of how the planes would respond to ground shaking from a large earthquake. Also, when Rockwell International was assembling the Space Shuttle at its Palmdale facility, it was concerned about the possibility of earthquake damage. After consultation with research workers, an earthquake study was made of the shuttle and the structure in which it was housed.

5. Large engineering design companies such as the Bechtel Corporation, which design such facilities as nuclear power plants, fossil fuel power plants, oil refineries, and chemical processing plants, have strong engineering departments that use results from earthquake engineering research in special applications. Chemical companies such as Dupont give special consideration to the earthquake design of important facilities and rely on research results for this purpose.

6. Large oil companies such as Exxon have strong engineering departments as well as research laboratories that give special consideration to the results of earthquake engineering research. The seismic design of large ground-based petroleum storage tanks is a particular example of how results from earthquake engineering research are put into practice. University research on the performance of tanks and the movement of the contained fluid during an earthquake enabled the forces and stresses in the tank structure to be calculated. These results led to the development of practical methods of design that have recently been incorporated in the American Petroleum Institute's codes in its publication *Seismic Design of Storage Tanks*. In the past, earthquakes

in the United States (Tehachapi in 1952, Alaska in 1964) and in Japan (Niigata in 1964, Tokachi-Oki in 1978) damaged tanks with consequent release of contents and destructive conflagrations.

7. Some of the larger insurance companies, for example Aetna Life and Travelers, make special studies of seismic risk as it influences earthquake insurance and company investments. The data for these studies come from the results of earthquake engineering research.

8. The results of earthquake research have also been applied to improving the seismic resistance of certain military facilities where earthquake damage could have serious consequences. However, much remains to be done.

Other examples of research applications could be cited; however, the foregoing are representative cases and show how widespread the application of research results has become in recent years.

A significant characteristic that enables high-technology organizations to use research results is the availability of a high level of scientific and engineering expertise that can (1) understand the nature of the special earthquake problem that is faced, (2) communicate directly with research workers to learn the latest results, (3) apply the data and information from research to solve the problem, and (4) put the solution in a form that the design engineers can understand and apply. Research workers cannot by themselves solve all the practical problems, because they usually do not know the special circumstances of the problem a company faces, nor do they know what a company's engineers can do. Therefore research workers must, in general, view the earthquake problem broadly and try to develop a body of basic information that can be applied to special problems as they arise.

Recommendations

1. During an earthquake any man-made object can be damaged if built without proper consideration of earthquake forces. Such objects include not only buildings and other structures but also manufacturing facilities, commercial facilities, equipment, large computing facilities, and so on, many of which are very important to the functioning of society. Earthquakes should be considered in the original design and construction of these items, at which time seismic safety can be achieved at relatively small cost. Continuing efforts should be made to bring to the attention of those responsible for planning and designing these items both the advantages to be gained by designing for earthquake forces and the availability of research results needed for this purpose.

2. A strong research effort should continue to be made to enhance the seismic safety of ordinary buildings that do not receive a special

seismic design, since these pose the greatest threat to public safety. However, the earthquake engineering research effort should be broadened to include the development of information needed for the seismic design of special facilities that are required for the orderly functioning of our industrialized society.

Earthquake Design of Structures

When buildings are severely damaged or collapse under the shaking of an earthquake, the earthquake engineering design was clearly not appropriate for the seismic conditions encountered. When a strong earthquake shakes a city, old weak buildings are usually severely damaged, but new buildings and new facilities are also damaged.

Postearthquake studies of damaged structures have revealed weaknesses that indicated deficiencies in the building code. This was the case, for example, with the severe damage suffered by the new Olive View Hospital building during the 1971 San Fernando earthquake and that suffered by the Imperial County Services building during the Imperial Valley earthquake of 1979, which resulted in complete loss since these structures had to be demolished. Very significant improvements in the requirements of the building code for earthquake design have resulted from studies of earthquake damage and from research on the performance of buildings during earthquakes. Instrumental

The new Olive View Hospital building was overstressed by the San Fernando earthquake. The damage was so severe that the structure was later demolished. The building had been designed according to the 1968 building code, but clearly the design was not adequate for the strong shaking it experienced.

recordings of strong ground shaking made during the past decade have clearly established that intense ground shaking can be much greater than once supposed by those responsible for drafting building codes. Although a building is more likely to experience moderately strong shaking than very severe shaking, the possibility of very intense ground shaking must still be taken into account, and the building must be designed to survive without becoming hazardous to its occupants.

The Building Code

The design and construction of ordinary buildings are governed by a building code, which is a legal document adopted by a government agency, usually the city government, that specifies minimum standards of construction. A large city such as Los Angeles has the expertise in its department of building and safety to prepare its own code, but most cities and towns in seismic regions adopt model codes such as the Uniform Building Code prepared by the International Conference of Building Officials (other standard building codes are also available for adoption). The earthquake requirements in the different codes are similar. However, many cities exclude the earthquake requirements when adopting a code.

The function of a building code is primarily to protect the public from death and injury and only partly to protect the investment of the owner. Therefore, in the event of very strong shaking, damage is expected but it should not be hazardous to the occupants of the building. The earthquake requirements in the building code specify simplified methods of analysis and design that determine the forces to be resisted and define the allowable stresses and strains. These requirements have changed over the years as research, including the study of actual earthquakes, has developed new knowledge. The changes in the building code therefore offer a history of the applications of earthquake engineering research to the design of ordinary buildings.

There is usually an appreciable time lag before relevant research results are reflected in building codes. This is partly because codes affect enormous monetary investments by the owners of buildings. Through their effects on the construction industry and its suppliers, changes in codes can have far-reaching ripple effects. In an effort to speed up the development of building codes, a report was prepared in 1978 entitled *Tentative Provisions for the Development of Seismic Regulations for Buildings*.* This 500-page report, which covers the

---

*Prepared by the Applied Technology Council with the support of the National Science Foundation and the National Bureau of Standards. The report was actually written by a group of committees composed of research workers and practicing engineers.

less seismic regions of the United States as well as the highly seismic regions, is much more detailed than the Los Angeles code, which covers the earthquake requirements in 11 pages. The report serves as an educational document and model and is a means of technology transfer.

To assess how earthquake engineering research has affected the seismic design of ordinary buildings, the earthquake requirements of the Los Angeles building code in 1933, when practically nothing was known about the problem, can be compared with the requirements in 1980, when much has been learned from research. Following the destructive March 10, 1933, Long Beach, California, earthquake, the first seismic requirements appeared in the Los Angeles code:

> a. Every building and/or structure and every part and/or portion thereof, and every ornamentation, appendage and appurtenance attached thereto, shall be proportioned, designed, constructed and/or erected to comply with the provisions of this section and to resist the horizontal forces provided in this section.
>
> b. The following formula shall be used to determine the horizontal force to be resisted as provided for in this section, to-wit: F equals CW; where F equals the horizontal force to be applied at the points and/or elevations as hereinafter specified in this section; C equals a numerical constant of the amount and/or value hereinafter provided in this section; and W equals the total dead load plus one half of the total live load required by this ordinance at and above the point or elevation under consideration.
>
> c. The amount and/or value of C in the foregoing formula shall never be less than eight-hundredths (.08) (Ordinance No. 72,968).

The 1933 code in effect stated that a building should be designed to withstand a horizontal thrust equal to a fixed percentage (8 percent) of its weight, without consideration of height, shape, rigidity, material of construction, use, seismic hazard, foundation conditions, or other factors. This simple earthquake requirement did result in a marked improvement in earthquake resistance, and as knowledge increased significant improvements were made to the code. The 1980 code is still a legal document with simplified rules for seismic analysis and design, but the rules are now more complex and reflect the real behavior of buildings during earthquakes in a way that the 1933 code did not.

A good example of the application of research can be seen in the 1980 edition of the Los Angeles code, which states (paragraph *d*, page 137) that every structure over 160 ft in height shall have strength sufficient to resist the effects of earthquakes as determined by a dynamic analysis, and that this analysis shall be based on the ground shaking prescribed for the site by a soil-geology-seismology report. This requirement of the code thus ensures that advanced methods of analysis and design will be employed for tall buildings, and that the design will be based on realistic ground shaking and realistic earthquake forces and stresses. This, of course, had already been done for 40- to 60-story buildings independent of the code; the successful performance of these buildings, as recorded by seismic instruments, led to the adoption of this requirement in the code. The design of these buildings is thus a direct application of the results of earthquake engineering research.

Present-day codes in the United States represent a major improvement in the earthquake design of ordinary buildings, and this is due entirely to research in earthquake engineering and to the study of actual earthquakes. U.S. codes have also served as a models in other seismic countries, many of which now have similar requirements in their codes.

Existing Buildings

Cities consist largely of buildings that were designed under earlier building codes, and it is important to assess how these might perform during future strong ground shaking. Such information is needed to make reliable risk assessments for U.S. cities. For example, this information is needed to assess the damage that a repetition of the 1906 earthquake would cause in San Francisco, or that a repetition of the 1811-1812 earthquakes would cause in St. Louis, Memphis, and other cities.

The useful life of a building tends to be prolonged far beyond that originally planned. At first a building may serve an affluent sector of society, and then in its later years provide low-cost housing and commercial space. Because of this, cities contain many old buildings that are low in earthquake resistance. Thus when a destructive earthquake hits a city in the western part of the United States, or in the Midwest or the East, the collapse of old buildings will cause the majority of casualties. Furthermore, many cities in the Midwest and East, although in seismic regions, have not adopted earthquake provisions in their building codes; therefore even some of the newer buildings may be deficient.

Some earthquake engineering research has examined the problem of old hazardous buildings, but the engineering problem is accompanied by social and economic problems. Although the Los Angeles County Earthquake Commission in its report on the 1971 San Fernando earthquake stressed the importance of the hazardous old building problem and recommended that it be completely solved in 10 years, not until 1981 did the City of Los Angeles adopt an ordinance and building code that required such buildings to be strengthened or demolished; it remains to be seen, moreover, how effectively this ordinance can be implemented. Continuing efforts should be made to develop cost-effective ways of strengthening these old structures and to educate owners of buildings, government officials, and the public about the need to solve this problem.

The problem of hazardous building also exists at military facilities. Important operations and equipment may be housed in structures that would be hazardous in the event of an earthquake, and critical equipment may itself be insecure in the event of strong shaking. In addition, earthquake damage to cities, industrial facilities, communications systems, etc., may adversely affect military facilities.

Planning of Buildings: Architectural Issues

When a building is being planned, many nonseismic considerations come into play. These include such things as the desired size, shape, appearance, function, and cost, considerations more immediate than the possibility of earthquake shaking at an indeterminate time in the future. Thus many important parameters of the building are fixed before the design engineer undertakes the seismic design, and since these strongly influence the dynamic response of a structure, the final building may not incorporate all the seismic resistance that the code originally envisaged. Damage in past earthquakes has often revealed unfortunate consequences of decisions during planning that might just as well have been different. This problem can be solved by better educating architects and owners about the effects of earthquakes.

Questions often arise about the earthquake safety of homes, that is, typical single-family dwellings, in highly seismic regions. These fall under the classification of nonengineered construction and derive their seismic resistance from requirements in the code that specify details of construction, such as the type of foundation, the size and number of foundation bolts, the type of bracing, the size and number of nails, the size of wood members, the size of wall panels, the steel reinforcing

These split-level houses were damaged by the 1971 San Fernando earthquake. In this type of structure, part of the house is built above the garage, so special bracing is needed to resist seismic forces.

bars in brick chimneys, and the connection of chimneys to structures. These requirements in the present code ensure that a house will be much more resistant to earthquakes than houses built before 1933, although this resistance is difficult to quantify. In recent earthquakes in California, the modern single-family dwelling has performed very well, demonstrating that such a house typically is not a hazard to life and limb even though very strong shaking might damage it.

Adequacy of Building Codes for Seismic Resistance

There is no question that present-day building codes result in much better design of buildings to withstand earthquakes than did the codes of 20 to 30 years ago. Modern buildings in most highly seismic regions should survive ground shaking that has a peak acceleration of 0.2 g without significant damage. Such intensity of shaking would occur, for example, 10 to 15 miles from the causative fault of an earthquake of magnitude 6.5, or 20 to 25 miles from the fault of a magnitude 7 earthquake. If subjected to stronger ground shaking, some of the buildings will probably be damaged. The severity of damage is difficult to estimate, however, because the resistance of buildings to earthquakes is influenced by such considerations as the desired architectural appearance, functional requirements, engineering judgment, materials of construction, and cost, and therefore different buildings can have different seismic resistances even though based on the same code. Also, adoption of a code by a community does not necessarily ensure that structures will have the specified earthquake resistance. The qualities of planning, engineering, construction, inspection, and so forth all influence the end product.

An important source of the data needed to advance earthquake engineering design is experimental research on material properties, structural elements and assemblages, and large-scale models of structures. The present level of experimental research in the United States is inadequate and compares very unfavorably with the experimental research being done in Japan. There should be a vigorous program of such research in the United States.

An important question about a building code is, "What factor of safety does the code provide against strong ground shaking?" That is, "What intensity of ground shaking will cause buildings designed to code levels to collapse or otherwise be hazardous to the occupants, and what is the probability that such strong ground shaking will occur?" The only way to determine this reliably is to undertake study projects of structures "as built" to include nonlinear dynamic effects, and in essence to carry out research projects on failure conditions, including the performance of structures during actual earthquakes. This is a major undertaking that has not as yet been attempted, but it should be done for a variety of buildings. From the viewpoint of improving the building code, research to analyze the failure of structures should be given a high priority. The information developed by such research would enable improvements to be made in the earthquake requirements of the building code that would eliminate building collapses and other hazardous damage.

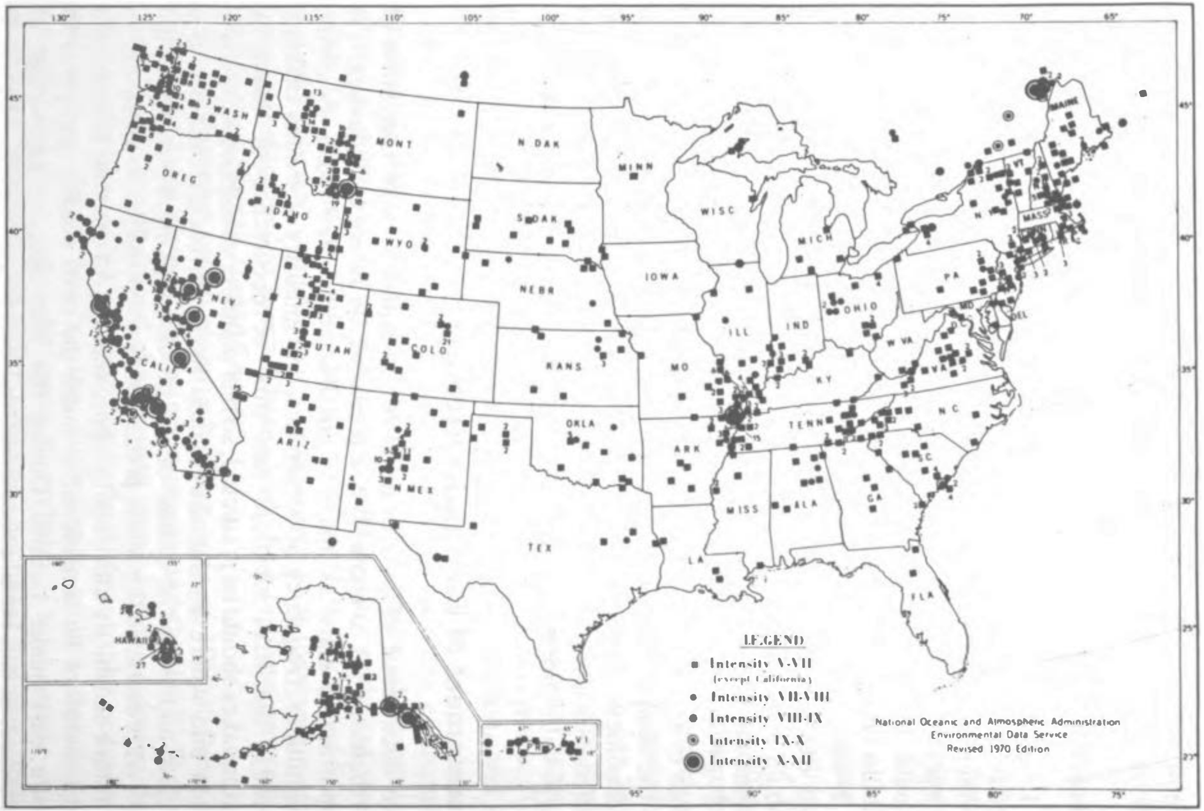
Recommendations

1. A much stronger program of experimental research than now exists is needed on material properties, the behavior of structural elements, and the performance of structures, all under dynamic conditions similar to seismic loadings. In this regard, earthquakes should be viewed as full-scale experiments, and thorough studies should be made of structures damaged by earthquakes.
2. Research should be done on the nonlinear response of structures that experience large strains during earthquakes, and this research should include analysis of how structural damage develops during an earthquake up to the point of structural failure.
3. Efforts should be made to synthesize research results and to put them in an easily understandable, simplified form that can be applied to the design of ordinary structures. In addition, continuing efforts at technology transfer should be made by means of lectures, short courses, technical papers, monographs, and books that would bring useful and up-to-date information to those engaged in the design of structures.

Assessment of Earthquake Hazard

The occurrence of past destructive earthquakes is an indication of earthquakes yet to come. When preparing for future earthquakes, it is important to know as much as possible about their likely locations, magnitudes, frequency of occurrence, and intensity of ground shaking. Ideally, the size, location, and time of occurrence of damaging earthquakes should be predicted, so that planners would know precisely when and where earthquakes would occur during the lifetime of a project and what the nature of the ground shaking would be at the site. At present, such precise prediction is not possible, so assessments of future seismicity can only be approximate. All relevant information must therefore be considered to make the most reliable estimates of future earthquake hazard. During the past decade, knowledge of earthquakes has greatly expanded and methods of assessing seismic hazard have greatly improved.

One source of data for assessing earthquake hazard is the historical record. For example, three great earthquakes occurred in 1811-1812



This plot of U.S. earthquakes shows those of intensity V and above on the modified Mercalli scale through 1970. Although large earthquakes occur less frequently in the Midwest and East than in the West, the seismic hazard in these regions should not be overlooked. SOURCE: National Oceanic and Atmospheric Administration, *Earthquake History of the United States*, U.S. Department of Commerce, Washington, D.C., 1970.

near New Madrid, Missouri, a great earthquake (magnitude 8.3) occurred in 1857 on the southern portion of the San Andreas fault, a large earthquake (magnitude 7.0) occurred in 1886 near Charleston, South Carolina, and a great earthquake (magnitude 8.2) damaged San Francisco in 1906. The last great earthquake (magnitude 8.4) in the United States occurred in Alaska in 1964. Unfortunately, the historical record in the United States extends only for the past 200 years or so, not for 2,000 years as in China or Italy, so hazard assessment must depend largely on an analysis of the occurrence of smaller, more frequent earthquakes. (Table 1 presents a selection of significant U.S. earthquakes.)

During the past 50 years a second source of data has emerged. Earthquake recordings made by sensitive seismographs can pinpoint the location of earthquakes and determine their magnitudes. This more complete set of data includes small, more frequent earthquakes as well as large, infrequent earthquakes and gives a much better picture of seismic activity. During the past decade, strong ground shaking recorded close to the fault has provided valuable information about the source mechanisms and nature of earthquake shaking.

In recent years seismologists have come to realize that the earth's crust contains a record of past earthquakes (paleoseismicity) that can be deciphered to provide valuable information for assessments of seismic hazard. Ground shaking is caused by the passage of seismic stress waves generated by a sudden slip on a fault. The displacement of the fault resulting from the slippage is therefore a record of that earthquake, and the size of the displacement indicates the earthquake's magnitude. When the fault displacement extends to the surface of the ground, it can be studied by trenching across the fault, by radiometric dating, and by other techniques. This can produce information about earthquakes that occurred as much as 100,000 years in the past; conversely, it may determine that the fault has not displaced during the past 100,000 years.

A study of the southern portion of the San Andreas fault opposite Los Angeles provided a very impressive application of this method of investigating faults. An earthquake of magnitude greater than 8 occurred on this segment of the fault in 1857, with surface displacements across the fault trace of 15 ft or so. Of course, a historical record of a single event cannot yield recurrence intervals for future events. Studies have now shown, however, that large earthquakes (fault displacements) have occurred on this segment of the fault 11 times in the last 1,700 years. This means that the average occurrence interval has been about 150 years. Since 125 years have passed since the last event, there is a high probability that the next event will occur during the coming 50 years. This has spurred the interest of professional organizations,

TABLE 1 A Selection of Significant U.S. Earthquakes

Year	Date	Location	Mag.	Int.	Remarks
1663	Feb. 5	St. Lawrence River region		X	Rockslides near Three Rivers, Quebec. Chimneys fell in Massachusetts Bay region.
1732	Sep. 16	St. Lawrence River region		IX	A large event.
1755	Nov. 18	Off Cape Ann, Massachusetts	6.0	VIII	Chimneys fell and buildings damaged in Boston and elsewhere. Many ships at sea were jolted.
1811	Dec. 16	New Madrid, Missouri	7.5	XII	Sequence of three large earthquakes. Caused major changes in topography. Affected two million square miles. Felt in Boston, 1,100 miles away. Because of remote location, only a few deaths.
1812	Jan. 23		7.3	XII	
1812	Feb. 7		7.8	XII	
1852	Nov. 9	Fort Yuma, Arizona		IX	Ground fissures. Many aftershocks.
1857	Jan. 9	Fort Tejon, California	8.3	XI	San Andreas fault offset 30 or 40 ft; fault ruptured for 250 miles. Because of remote location, only one known death.
1868	Apr. 2	Island of Hawaii	7.7	X	Volcanic earthquake on south slope of Mauna Loa. Much damage to houses. Tsunami killed 46 people.
1868	Oct. 21	Hayward, California	7.5	IX	Extensive surface rupture on Hayward fault. 30 deaths. Many aftershocks.
1872	Mar. 26	Owens Valley, California	8.5	XI	One of the strongest U.S. earthquakes. Fault scarp 20 ft high. 27 deaths.
1886	Aug. 31	Charleston, South Carolina	7.0	X	Greatest earthquake in eastern United States. Several aftershocks. Much building damage. 110 deaths.
1895	Oct. 31	Charleston, Missouri		VIII	Chimneys fell. Earthquake felt from Canada to Louisiana.
1899	Sep. 3	Alaska; near Cape Yakataga	8.3	XI	Ground uplifts; seiches; people unable to stand.
1906	Apr. 18	San Francisco, California	8.3	XI	San Andreas fault ruptured for 270 miles. Ground offset 21 ft. About 700 deaths during earthquake and fire.
1915	Oct. 2	Pleasant Valley, Nevada	7.6	X	Large fault displacements in an unpopulated region. Adobe houses destroyed.
1921	Sep. 29	Elsinore, Utah		VIII	Chimneys toppled. Many aftershocks.

TABLE 1 A Selection of Significant U.S. Earthquakes—(*Continued*)

Year	Date	Location	Mag.	Int.	Remarks
1925	Feb. 28	St. Lawrence River region	7.0	VIII	Felt over a wide area, south to Virginia and west to the Mississippi River. Little damage.
1925	June 27	Manhattan, Montana	6.7	VIII	Buildings damaged. Rockslides.
1925	June 29	Santa Barbara, California	6.3	IX	Much building damage. Sheffield Dam failed. 13 deaths.
1931	Aug. 16	Valentine, Texas	6.4	VIII	Buildings damaged; chimneys fell.
1932	Dec. 20	Cedar Mountain, Nevada	7.3	X	Region was uninhabited at the time. Many ground fissures.
1933	Mar. 10	Long Beach, California	6.3	IX	Much damage to buildings, especially schools. 120 deaths.
1934	Jan. 30	Excelsior Mountains, Nevada	6.5	VIII	Minor surface faulting. Minor damage in Mina.
1934	Mar. 12	Kosmo, Utah	6.6	VIII	Many ground changes (fissures, rockslides, new springs). Chimneys fell; 2 deaths.
1935	Oct. 18	Helena, Montana	6.2	VIII	Many buildings damaged; 2 deaths. Strong aftershock on Oct. 31 (magnitude 6.0) caused 2 additional deaths.
1940	May 18	El Centro, California	7.1	X	Large ground displacements along Imperial fault. Much building damage. 9 deaths. First important accelerogram for engineering use.
1949	Apr. 13	Olympia, Washington	7.3	VIII	Many buildings damaged; 8 deaths.
1952	July 21	Kern County, California	7.7	XI	Railroad tunnel collapsed; buildings damaged at Tehachapi. Many large aftershocks. 12 deaths.
1954	July 6	Fallon, Nevada	6.6	IX	Damage to canals and roads east of Fallon. Minor building damage.
1954	Aug. 23	Fallon, Nevada	6.8	IX	Surface ruptures east of Fallon.
1954	Dec. 16	Fairview Peak, Nevada	7.1	X	Large fault scarps. Because of remote location, no deaths. Reservoir in Sacramento, 185 miles away, badly damaged by sloshing water.
1954	Dec. 16	Dixie Valley, Nevada	6.8	X	This earthquake occurred four minutes after preceding one; location was 40 miles north.

TABLE 1 A Selection of Significant U.S. Earthquakes—(*Continued*)

Year	Date	Location	Mag.	Int.	Remarks
1958	July 9	Lituya Bay, Alaska	7.9	XI	Earthquake on Fairweather fault. Massive landslide created a huge water wave. 5 deaths.
1959	Aug. 17	Hebgen Lake, Montana	7.1	X	Huge landslide dammed Madison River and formed "Earthquake Lake." Large seiche in Hebgen Lake. Houses and roads damaged. Many aftershocks. 28 deaths.
1964	Mar. 27	Prince William Sound, Alaska	8.4	XI	Known as the Good Friday earthquake. Severe damage to Anchorage and many other cities. Landslides. Great tsunami damaged many coastal cities in Alaska and killed 11 people in Crescent City, California. 131 deaths.
1965	Apr. 29	Puget Sound, Washington	6.6	VIII	Buildings damaged in Seattle, Tacoma, and vicinity. 6 deaths.
1966	June 27	Parkfield, California	5.5	VII	Large ground accelerations (0.5 g).
1968	Apr. 8	Borrego Mountain, California	6.5	VII	On Coyote Creek fault. Surface fractures. Undeveloped area; minor damage.
1971	Feb. 9	San Fernando, California	6.5	XI	Several buildings and highway bridges collapsed. Many instrumental records obtained. 58 deaths.
1975	Mar. 28	Malad City, Idaho	6.1	VIII	Minor damage to buildings.
1975	June 30	Yellowstone National Park, Wyoming	6.4	VII	Rockfalls; new geysers formed.
1975	Nov. 29	Island of Hawaii	7.2	VIII	Volcanic earthquake near Kalapana (on south coast). Much building damage. Landslides. Tsunami caused damage along coast. Two deaths.
1978	Aug. 13	Santa Barbara, California	5.7	VIII	Extensive building damage; train derailed.
1979	Oct. 15	Imperial Valley, California	6.7	VII	Extensive surface rupture on Imperial fault. Damage to buildings and canals.
1980	May 18	Mount St. Helens, Washington	5.2		Volcanic earthquake. Preceded a major eruption that killed 60 people.
1980	July 27	Northern Kentucky	5.3	VII	Minor building damage.

TABLE 1 A Selection of Significant U.S. Earthquakes—(*Continued*)

Year	Date	Location	Mag.	Int.	Remarks
1980	Nov. 8	Eureka, California	7.4	VII	Off the coast. Highway bridge collapsed; moderate building damage. Five people injured.
1982	Jan. 18	Franklin, New Hampshire	4.8	VI	Felt throughout New England.
1982	Jan. 20	Naylor, Arkansas	4.5	V	Many small earthquakes during a two-week period. (Naylor is 28 miles north of Little Rock.)

NOTE: This compilation is not complete since there is no historical record of large earthquakes that may have occurred in the midwestern and western United States prior to 1800.

SOURCE: James M. Gere, *Earthquake Tables*, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, Stanford, California, 1982.

government agencies, and public groups in making preparations. Unfortunately, similar information is not yet available for earthquakes in the midwestern or eastern United States because the geological evidence is more obscure and the amassing of data is more difficult.

Since it is not possible to predict the size, location, and time of damaging earthquakes precisely, and since the data on occurrences of earthquakes are incomplete, hazard assessments must rely heavily on probabilistic statements about the likelihood of future earthquakes and ground shaking. Although recent research has produced many developments in the probabilistic treatment of earthquake data, many questions have arisen about how to interpret probabilistic statements properly. One question concerns the maximum earthquake, that is, What is the maximum size of earthquakes that might occur in a region during a specified time? This is a matter of great practical importance that deserves further study.

A special problem in earthquake engineering that has received increasing attention in recent years concerns earthquakes that have been triggered by filling of reservoirs behind dams. The filling of large reservoirs usually sets off a number of small earthquakes in the vicinity, but in some cases damaging earthquakes of magnitude 6 or so have followed. In two cases (the Koyna Dam in India and the Hsinfengkiang Dam in China) large concrete dams were alarmingly damaged, and both of these dams were in regions of relatively low seismicity. Thus the curious situation exists in which construction produces earthquakes that damage the structure. This is a point of great practical interest, but present knowledge unfortunately cannot identify sites where the filling of reservoirs will, or will not, induce earthquakes. This is clearly a matter that needs further study.

Recommendations

1. Studies should continue to be made of the frequency of occurrence and geographical locations of earthquakes of various magnitudes, with the objective of improving the reliability of seismic hazard assessments. In parallel with these studies, research should be carried out to improve probabilistic methods of analyzing seismic data and quantifying seismic hazard.
2. Research should specifically investigate the largest earthquake that might occur in a seismic region and its likelihood of occurrence, for this information has an important bearing on seismic safety. Attention should be particularly given to the differences between eastern and midwestern earthquakes and earthquakes that occur in the West so as better to quantify the seismic hazard posed by the occurrence of larger earthquakes in the East and Midwest.
3. There is a need to improve methods of interpreting the geological record to learn about the occurrence of larger earthquakes in the past, which can then be used to assess future seismic hazard. This research should also include studies of reservoir-induced earthquakes so as better to quantify this hazard to dams.

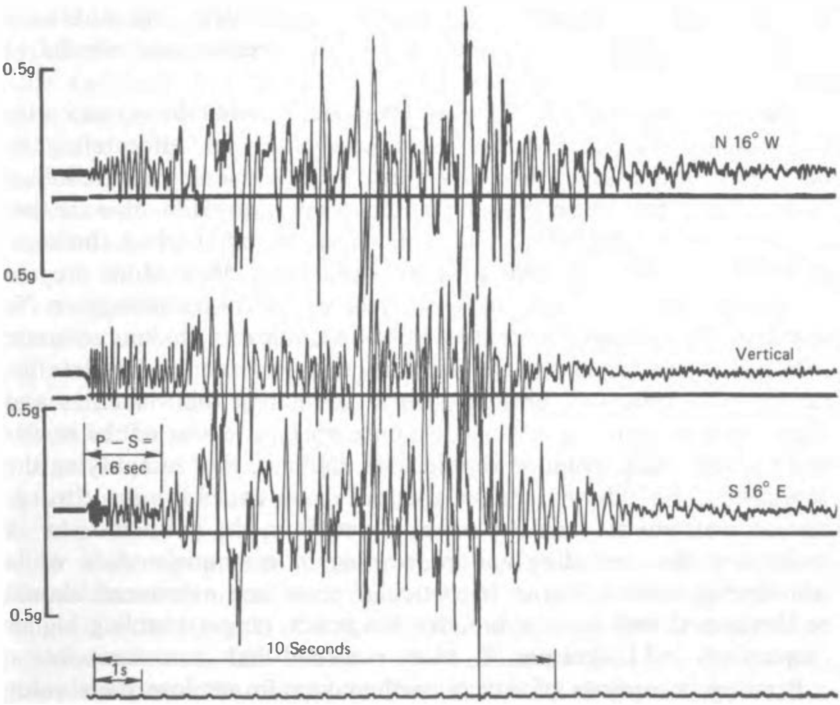
Recording and Analyzing Earthquake Ground Motions

The recording of strong earthquake ground motion provides the basic data for earthquake engineering. Without a knowledge of the ground shaking generated by earthquakes, it is not possible to assess hazards rationally or to develop appropriate methods of seismic design.

The instruments for recording strong ground shaking have some unique requirements. When an earthquake occurs, the recording instruments should be in appropriate locations for recording the desired ground shaking. Also, because earthquakes occur infrequently, instruments must be able to remain quiescent for long periods, sense the onset of shaking, and then turn on and record the motions.

Almost all countries with seismic regions now use strong-motion instruments developed and manufactured in the United States, though Japan and New Zealand have developed their own accelerographs. Particularly valuable records have been obtained from the 1968 Tokachi-Oki, Japan, earthquake; the 1971 San Fernando, California, earthquake; the 1979 Imperial Valley, California, earthquake; the 1979 Montenegro, Yugoslavia, earthquake; and the 1980 Campania-Basilicata, Italy, earthquake.

In the United States over about the last decade, federal, state, and local government agencies, public utilities, research laboratories, and building owners have installed many accelerographs. The U.S. Geo-



This accelerogram was recorded above the causative fault at the center of energy release during the 1971 magnitude 6.5 San Fernando earthquake. This very intense ground shaking was recorded on the side of a steep hill. More than $500 million (1971 dollars) in damage was caused by this intermediate-sized earthquake.

logical Survey (9 percent) and the California Division of Mines and Geology (13 percent) have instrument programs that are mainly for research purposes. The remaining 78 percent of the accelerographs have been installed for special purposes, with no overall coordination or planning. An overall study of the strong-motion instrument program in the United States should be made to prepare guidelines for the future development of instruments, for the installation of instrument networks and arrays, for the avoidance of unnecessary duplications, and so on. The installation of recording instruments in highly seismic regions in other countries that are not now instrumented should also be considered.

During the past decade strong-motion accelerographs have been installed in structures and have recorded their vibrations during earthquakes. These instrumental data showing how the structures responded to ground shaking are of great value to earthquake engineers. For example, accelerographs recorded the motions of the Imperial County Services building during the 1979 Imperial Valley earthquake while the structure was vibrating to the point of severe structural damage. Such recordings of movements are valuable, but additional instruments should be installed to record stresses and strains at significant points in structures.

After the strong ground motion has been recorded during an earthquake, the problems of processing, disseminating, and interpreting the data remain. The recorded data must be processed to put it into a form suitable for dissemination to users. One of the difficulties is that no data are available until an earthquake occurs, after which there are many records and a demand for rapid processing. Most of the present instruments are of the analog type, making optical recordings on 70-mm film. Processing thus involves developing the film, making accurate enlarged prints, digitizing the accelerograms, correcting the data for the characteristics of the instrument, calculating the velocities and displacements, and calculating response spectra. Some of the newer instruments being installed record data digitally, thus simplifying the processing. But these require greater initial expenditures. Strong-motion instruments need to be examined from the point of view of optimizing the recording and processing of earthquake data while considering the overall cost. In particular, recording instruments should be developed that have a broader frequency range, enabling higher frequencies and longer periods to be recorded than is now possible.

Because recordings of strong earthquakes do not lose their value with time, the trend is toward an ever larger data base. This raises problems of disseminating the data. The potential user of data must be able to identify what information is available and obtain copies in a reasonably short time. At present there is no national program of data dissemination. The U.S. Geological Survey and the California Division of Mines and Geology maintain instruments and disseminate data, but many instruments are not under the supervision of these two groups. A more coordinated program to collect and disseminate all strong-motion data is needed so that users can know what is available and how to obtain it. This is not only a national problem but a world problem, for there is now no international coordination of strong-motion data.

Improved national and international programs of data collection and dissemination would greatly enhance the interpretation of strong-motion data. The more data that are available, the more reliable can be the interpretation. This also applies to ancillary data, such as physical characteristics of local soils where ground motion has been recorded and travel paths of seismic waves as they progress from their source to recording points.

Strong-motion seismology, or engineering seismology, is the study of potentially destructive ground shaking. It seeks to develop sufficient understanding of the earthquake process so that reasonable predictions can be made of the nature of strong ground shaking that earthquakes of different magnitudes, at varying distances, and in regions of different soils and local geology would produce. Such a capability would be very helpful for earthquake engineering, since the present strong-motion data base is still fragmentary. The construction of critical facilities, such as nuclear power plants and LNG storage tanks, in various parts of the country has created an urgent demand for reliable estimates of possible ground shaking, and in particular for estimates of upper bounds to the intensity of ground shaking. Only improvements in strong-motion seismology and the occurrence of large earthquakes can provide this information. At present, strong-motion data for the midwestern and eastern parts of the United States are almost nonexistent, and this lack of data adds uncertainty to estimations of the effects of future earthquakes.

A network is a group of instruments in a region that are stationed at uncoordinated locations, for instance the basements of buildings, the abutments of dams, electrical power plants, and other places. An array of strong-motion instruments, in contrast, is installed at coordinated locations to optimize the recording of desired information. The simplest array consists of a number of instruments spaced along a line perpendicular to the causative fault of an earthquake. These can provide information on how the ground shaking changes with distance from the fault. A more complicated array may have instruments located at grid points near the causative fault and also at several depths beneath the surface of the ground. Such a three-dimensional array provides information not only on ground shaking at the surface but also on motions at depth. This information provides valuable data on the propagation of seismic waves, which enhances the ability to estimate surface shaking in future earthquakes. It also reveals motions that structures with deep foundations might experience. The desirability of installing such arrays in the highly seismic regions of the United States and the world should be studied, and they should be installed if the studies so indicate.

A key element in assessing earthquake hazard is a good data base of recorded strong earthquake ground motions. For example, when a magnitude 7 earthquake occurs, records should be obtained of the ground shaking close to the fault and at increasing distances from the fault in parallel and perpendicular directions. In this way a more or less complete picture can be obtained of how ground shaking varies across space. To date, reasonably complete pictures have been obtained for only two earthquakes, both of magnitude 6.4. Larger earthquakes have yielded only fragmentary information. Vigorous efforts should be made to obtain the needed recordings when future destructive earthquakes occur.

Recommendations

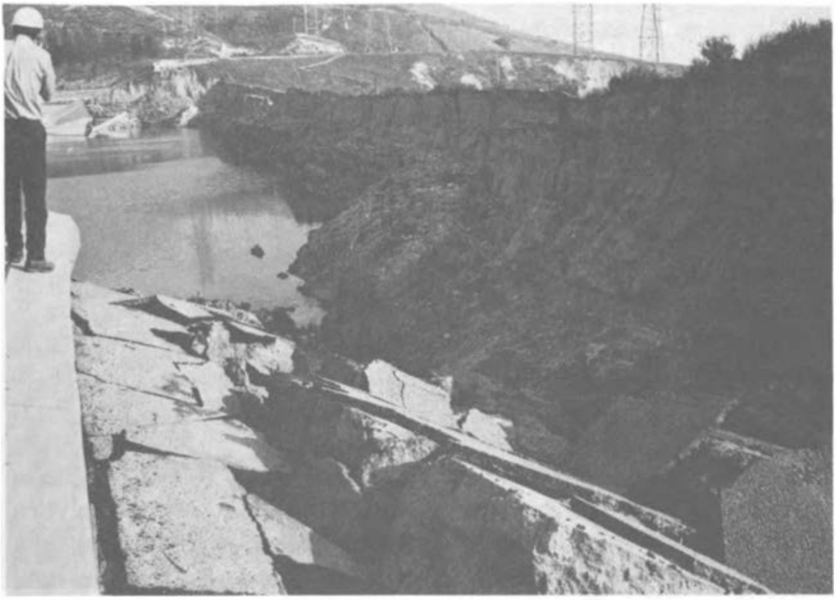
1. A strong effort should be made to record destructive ground shaking of future earthquakes. Better methods of forecasting these motions should be developed, and careful assessments should be made of seismic probabilities. Appropriate instrument networks or arrays should then be installed to record the strong shaking of large earthquakes.
2. The capabilities of modern instrumentation and equipment for recording and processing earthquake data should be used more fully. The data output of these devices should contain all potentially valuable information in a form that is readily usable by those who wish to study it.
3. An entity such as a U.S. National Committee on Earthquake Engineering Research should be organized to plan and coordinate a long-range earthquake engineering research effort. In particular, a National Strong-Motion Program is needed to coordinate the various users of strong-motion data and those organizations that install, maintain, and process the data from strong-motion networks. The availability of strong-motion data should be increased not only in the United States but worldwide.

Soil Mechanics and Earth Structures

For structures founded upon the earth, the ground beneath must be able to withstand the forces applied to it by the structure. In addition, earth structures such as dams and embankments must be designed and constructed so that they will not fail due to the action of earthquakes. Earthquake shaking has often caused highly damaging soil failures in the past. For example, many landslides occurred during the 1964 Alaska earthquake, and a number of these were very damaging. In Anchorage the Turnagain Heights landslide destroyed 35 homes, and at the waterfront town of Valdez an underwater landslide destroyed the port facilities and generated a very damaging waterwave. During the 1925 Santa Barbara, California, earthquake, Sheffield Dam, an earth structure, failed completely, releasing the water in its reservoir. During the 1971 San Fernando earthquake the upstream slope of the earthen Lower San Fernando Dam slid beneath the water, and the dam was close to releasing the contents of its reservoir upon the 80,000 persons living below. During the 1964 Niigata, Japan, earthquake the sandy water-filled soil underlying the city underwent extensive liquefaction and was not strong enough to support structures, resulting in several billion dollars of damage (1982 dollars) due to settlement.

These cases provided a strong incentive for studying the behavior

This photograph of the Lower San Fernando Dam, taken a week after the 1971 earthquake, shows the extensive residential area below the dam. Eighty thousand residents were evacuated for three days until the reservoir was lowered to a safe level.



The upstream slope of the Lower San Fernando Dam slid beneath the water during the 1971 San Fernando earthquake, leaving just 4 ft of freeboard. This 140-ft-high earth dam was constructed prior to 1920 at a time when earthquake hazard was not considered.

of soil and the dynamics of earth structures during earthquakes. Much progress has been made during the last decade in understanding such behavior and in developing sound concepts and procedures for designing new structures and strengthening existing facilities that are hazardous. This progress has resulted from studies of destructive earthquakes, from fundamental examinations of the stress-strain behavior of soils during earthquakes, from new methods of dynamic analysis that use powerful computers, from improved methods of evaluating soil properties, and from comparisons of the predicted responses of earth structures and soil deposits with observations and measurements made during actual earthquakes. Because there are many different kinds of soils, which have been deposited under different conditions and contain different amounts of moisture (factors that strongly influence their physical properties), studying the engineering properties of soils is much more complex than is studying the engineering properties of, say, steel.

When seismic waves approach the base of a structure, they must travel through the layers of soil overlying the bedrock, and the behavior of the soil can modify both the seismic waves and the response of the structure. For example, a very soft soil, such as that underlying Mexico City, may behave like a bowl of jelly, causing the surface of the ground to move much differently than if the soil were firm. In addition, the flexibility of the soil beneath a structure will affect the vibrations of the structure. Research during the past decade has markedly advanced knowledge about these effects, and the seismic requirements of building codes have been modified to reflect this increased knowledge.

Soil liquefaction results when a sandy soil with a high water table is subjected to earthquake action. This causes a reorientation of the soil particles and closer packing, thus adjusting the load from the soil to the water, with consequent loss of strength. Twenty years ago very little was known about soil liquefaction during earthquakes, and its potential for damage was not widely recognized. Then the disastrous Niigata, Japan, earthquake of 1964 forcefully brought the enormous potential for damage from liquefaction of soils to the attention of the engineering profession. Since then, signs of liquefaction have been observed in most large earthquakes and laboratory research has been done to elucidate this behavior. The research has demonstrated that an important feature of liquefaction is the building up and dissipation of pore water pressure during an earthquake. Consequently, analytical procedures have been developed that can explain how this phenomenon occurs and what might be done to control it.

Retaining walls that hold back earth, quay walls in harbors, and abutments in bridges have frequently been damaged by strong earthquake ground shaking because of excessive pressure exerted by the earth behind the wall. In recent years research has developed a new approach to the design of such structures, one based on a more realistic evaluation of the behavior of the earth-wall system. This procedure has been incorporated into the new *Seismic Design Guidelines for Highway Bridges* of the American Association of State Highway and Transportation Officials.

Past earthquakes have often extensively damaged buried pipelines in soft soils. Buried waterlines, sewerlines, and gaslines are stressed by seismic waves passing through the surrounding ground; in addition, soil consolidation, slumping, and sliding can produce damage. At present experimental data on the actual performance of buried pipelines during earthquakes are lacking; this complex problem requires additional research.

When major earthquakes occur in regions where the surface of the ground is sloping or where there are hills or mountains, landslides, rock falls, and avalanches are frequently generated. Urban areas in

The city of San Francisco burned out of control the day after the April 18, 1906, earthquake. The city of Tokyo similarly burned after the September 1, 1923, earthquake; in that city over 300,000 dwellings were burned or shaken down. These are two instances of earthquakes putting fire departments out of action and causing conflagrations. In both cities damage to underground pipes cut off the water suppy. It is of prime importance to have the fire-fighting system functional after an earthquake, especially when conditions are favorable to the spread of fires.

seismic regions should assess the hazards of potential landslides and other soil failures, and this information should be used in zoning. Recent years have seen some advances in making such assessments of hazard. But because the hazard depends on the properties of the ground itself and on the anticipated severity of the ground shaking as well as on the slope of the ground's surface, the problem is very difficult. Better methods of assessing such hazards are needed, ones that are sufficiently reliable to be acted upon by local governments.

Soils are complex particulate media whose physical properties under large strains and stresses are not simple. To develop methods for determining seismic resistance, a good understanding of these properties is important. Recent years have produced advances in studying soil properties in the laboratory and in the field, and methods of analysis have been developed to study the behavior of soils under varying stresses, but further research is needed.

During the last decade or so, important advances have been made in identifying potentially hazardous soils and soil structures, and methods of analysis and design are now much more realistic and reliable. However, additional research is required, particularly where critical facilities or large areas may be involved.

Recommendations

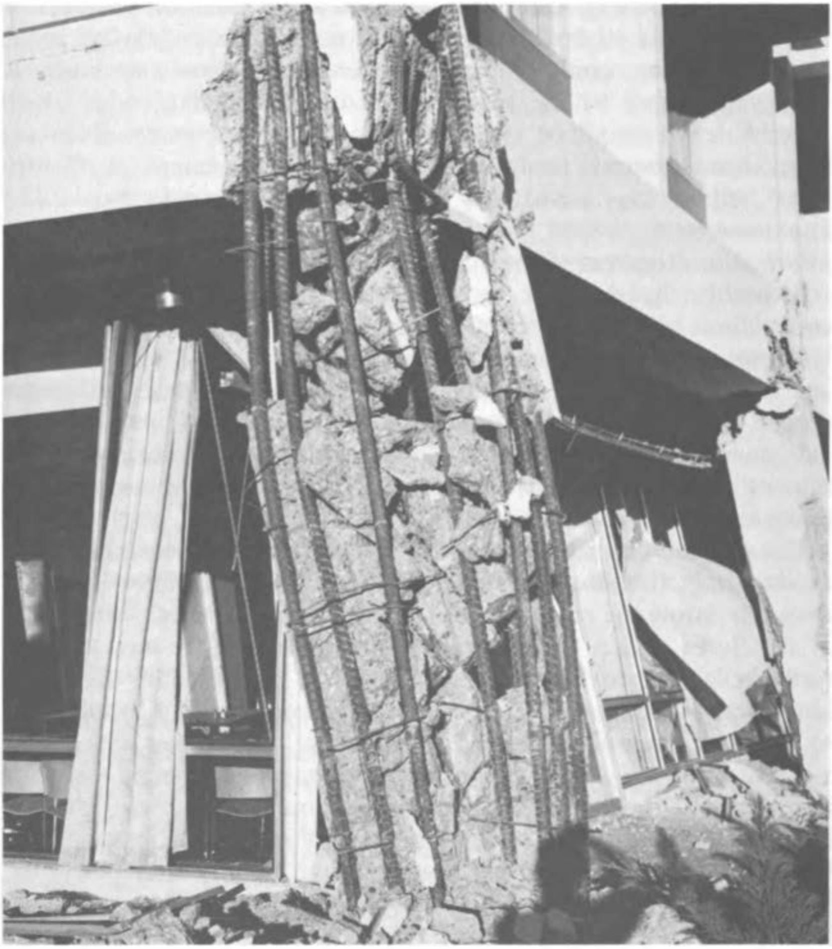
1. The performance during earthquakes of soils and soil structures and soil-structure interaction should be studied by measuring and recording displacements, deformations, and stresses under conditions like those produced by earthquakes. These studies should include both experimental laboratory tests and field investigations. Centrifuge techniques, shaking tables, vibration generators, and other devices should be used to reproduce suitable dynamic stresses and strains.
2. Studies should be made of the response of large-scale structures, such as earth dams, under actual earthquake conditions. These observations should be correlated with the results of laboratory experiments and theoretical analyses.
3. A two-pronged attack should be made to (a) develop better methods of analyzing the dynamic stresses and strains and failure conditions of soils and (b) to synthesize and simplify the results of research to make them easier to apply in practice.

Analytical and Experimental Structural Dynamics

Before a building is constructed, decisions must be made as to the size and shape of each member, the composition of each member, and the interconnections between members. If these decisions are not correct, the building may be unsafe. They are based on analyses of the stresses and strains that specified forces, such as gravity, wind, and earthquakes, would produce. The design of ordinary structures is usually governed by the requirements of the building code, which specify rather simplified forces for wind and earthquake. Even so, rather complex stress analyses must be made. For example, a 10-story office building may have 1,000 beams and columns and almost 2,000 interconnections whose stresses and strains must be analyzed. This information, together with a good knowledge of material properties, will enable the designer to decide on the correct members and connections. In the case of special structures, such as high-rise buildings, dams, long-span bridges, nuclear power plants, LNG tanks, and offshore platforms, dynamic analyses using specified earthquake ground shaking are customarily made to obtain realistic values of the maximum stresses, strains, and displacements. The seismic design thus relies on the ability to calculate structural performance reliably under the action of realistic earthquake forces.

Because the calculation of dynamic stresses and strains plays such an important role in seismic design, it has been the subject of much research during the past decade. Dynamic analyses, using computers, of structures excited by moderately strong shaking are now satisfactorily reliable, provided that the structure is not highly complex. However, a structure must be able to survive even if it is subjected to very intense ground shaking. In this case the stresses and strains will exceed the elastic limits, and calculations must then be made for a nonlinear structure, which is a much more complicated problem. During the past decade the understanding of nonlinear vibrations and the ability to make such calculations have improved significantly. However, this difficult problem is far from solved, mainly because the physical properties of a system change continually during inelastic vibrations. The recorded response of the Imperial County Services building during the 1979 Imperial Valley earthquake strikingly demonstrated how the response of a structure to ground shaking changes as its structural parts are damaged. This is the only case where the motions were recorded in a structure that suffered increasingly severe damage during the ground shaking, and there is an urgent need for more recordings made in buildings that are significantly damaged by an earthquake.

The ground beneath a structure is not rigid, and its deformation under forces influences the dynamic behavior of the structure. When a structure vibrates during an earthquake, the deformability of the ground permits the base of the structure to rotate and displace horizontally, and analyses of earthquake response must take this into account. This effect is small for light flexible structures on hard ground,



This reinforced column was shattered by earthquake forces. Research has developed methods of design that will prevent such columns from shattering.

but it becomes increasingly important for more massive rigid structures on softer ground. The response to an earthquake of a massive rigid containment structure of a nuclear reactor can be very significantly affected. Considerable research has been done in recent years on this problem of soil-structure interaction and its effect on dynamic response, and quite reliable dynamic analyses can be made if the ground is treated as an elastic medium. If the ground exhibits significant nonlinear characteristics, however, the problem becomes much more complex and further research is needed to develop satisfactory methods of analysis.

A major source of difficulty in earthquake engineering is that each building is a custom-designed structure. If buildings were mass produced so that only a few types of structure needed to be studied, the problem would be much simpler. As it is, buildings of widely varying sizes and shapes and of different materials must be considered. Extensive laboratory research is thus required to clarify the physical properties of the materials, the structural elements, and the complete structures. Rarely is it possible to test a full-scale structure under realistic conditions of stress and strain; therefore it is necessary to test models of structures and structural elements in the laboratory. The information provided by these tests is of great importance in developing reliable methods of earthquake-resistant design.

A significant analytical development in recent years has been the study of the physical properties of structures by analyzing the motions recorded in them during earthquakes. This method, called system identification, has made it possible to make very reliable estimates of a structure's physical properties when the recorded vibrations are linear or only slightly nonlinear. Further research is now under way on possible extensions of this method to more strongly vibrating structures.

Shaking tables, which can subject models of structures to realistic earthquake shaking, have provided valuable information on structural dynamics. Some very large shaking tables are now being constructed in Japan that will be able to test large models with shaking that corresponds to a very large earthquake.

Recommendations

1. Dynamic structural analysis, a key element in the seismic design of structures, should continue to be developed to handle the response during earthquakes of complex structures subjected to large, inelastic strains up to the point of failure. Methods of theoretical analysis, experimental investigation, and digital computation should be developed in parallel.
2. A strong program of experimental investigation is needed to provide the necessary information on the physical properties of materials, structural elements, and full-scale structures under earthquake conditions.
3. Special studies should be made of the actions of soils upon structures, including that of short-wavelength seismic waves upon the foundations of extended structures and that of dynamic deformations of the soil upon structural behavior.
4. Appropriate instrumentation should be installed to record the motions and deformations of real structures during actual earthquakes, and improved methods should be developed for identifying the physical

properties of structures as they vary during the ground shaking of a large earthquake.

Seismic Interaction of Structures and Fluids

The behavior during earthquakes of structures that contain fluids, are surrounded by fluids, or are immersed in fluids is strongly influenced by the interactions between the structure and the fluid. Such structures include dams, liquid storage tanks, offshore structures, and coastal structures that interact with water waves generated by earthquakes. In all of these cases, the forces exerted by the fluid upon the structure can produce large and potentially damaging stresses.

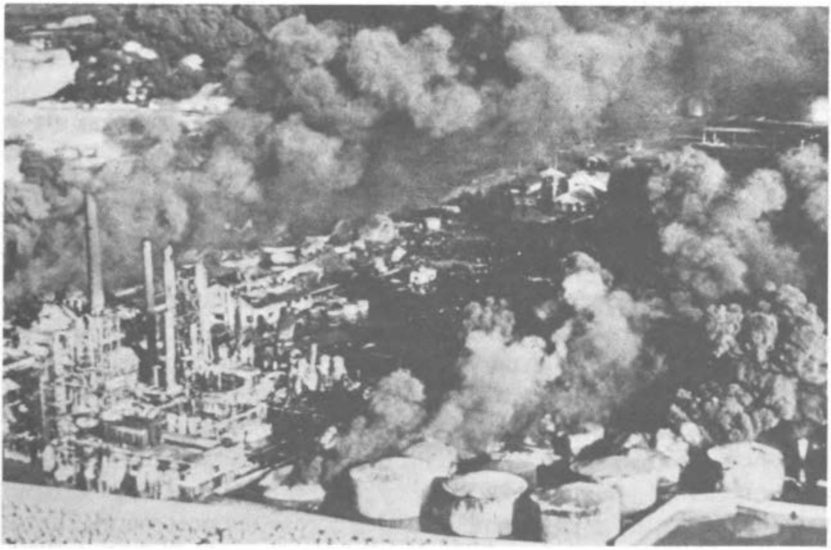
During an earthquake the motion of the ground moves a dam against the water in the reservoir, generating water pressures against the face of the dam. In addition, the vibrations of the dam induced by the earthquake interact with the water, producing additional dynamic fluid pressures. In recent years three major concrete dams have been strongly shaken by earthquakes of approximately 6.5 magnitude, and in two cases serious damage resulted. A 338-ft-high concrete gravity dam in Koyna, India, was severely cracked. A concrete buttress dam in Hsinfengkiang, China, was also alarmingly cracked. Pacoima Dam, a concrete arch structure, was intensely shaken by the San Fernando earthquake, but the reservoir was only partly full and the dam was not damaged.

During the past decade or so, very important developments have been made in assessing seismic hazard for dams, in making dynamic analysis of dams excited by earthquakes, and in producing more reliable seismic designs. These advances, which were made possible by earthquake engineering research, are now used in the United States by the Bureau of Reclamation, the U.S. Army Corps of Engineers, and the California Department of Water Resources. They are also now being applied in other parts of the world.

Although the modern methods of seismic analysis and design are a great improvement over the old equivalent static force methods, much remains to be learned. The vibratory motions of a dam structure during very strong ground shaking have never been recorded, although this is needed to check the methods of analysis and design. A dam is a three-dimensional structure with large dimensions, and ground shaking can presumably have quite different characteristics over the extended area of a dam's foundation; unfortunately, the recordings needed to understand these variations have never been made. For dams of more complicated shapes or with complicated construction, very extensive computer calculations must be made with the material properties throughout the dam precisely specified. At present, these calculations are research projects in themselves. There is thus a need to develop practical, as well as reliable, methods of seismic analysis and design. Such methods should also apply to studying the safety of existing dams.

Liquid storage tanks are important elements of modern industrialized society. Water storage tanks serve the needs of a city and provide for fire fighting; petroleum storage tanks are a vital element of a functioning urban community; chemical fluid storage tanks are widely used throughout industry; and LNG storage tanks will be of increasing importance in the future. Tanks of increasingly large size, at present 300 ft in diameter and 60 ft high, are being constructed. During an earthquake the ground motion vibrates the tank against the fluid, and the resulting pressures cause the fluid to slosh, producing pressures against the wall of the tank that vary more slowly. In recent years research has developed methods of seismic analysis that give a realistic picture of the stresses and strains produced in a tank during an earthquake. Results of this research have now been incorporated into the American Petroleum Institute's *Seismic Design of Storage Tanks*.

Liquid storage tanks have failed in many past earthquakes. For example, destructive fires resulted from damage to petroleum storage tanks in the 1952 Tehachapi, California, earthquake, the 1964 Alaska earthquake, the 1964 Niigata earthquake, the 1968 Tokachi-Oki earth-



Damage to oil storage tanks during the 1968 Tokachi-Oki, Japan, earthquake led to the release and ignition of petroleum products, resulting in destructive fires.

quake, and others. Damage to tanks from earthquakes has included buckling of the tank walls, buckling of the roof, cracking of welds, tearing of plates, breaking of connections, and even complete collapse. Methods of seismic analysis have not yet been developed to the point where they can reliably estimate tank failures. The motions of a large tank during an earthquake have never been recorded, and in particular they have never been recorded for a tank shaken hard enough to be damaged. The use of LNG storage tanks, which are critical facilities that require more refined and reliable methods of seismic hazard assessment, analysis, and design than do ordinary tanks, provides motivation for additional research.

In recent years offshore drilling for oil in seismic regions has posed the problem of the seismic analysis and design of large structures of unusual form standing in relatively deep water. Earthquake engineering research has provided the information for making detailed dynamic analyses and designs of offshore structures, and this information is the basis for the seismic design criteria that appear in the American Petroleum Institute's *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms* and in the American Concrete Institute's *Guide for Design and Construction of Fixed Offshore Concrete Structures*. However, to date, no recordings have been made of earthquake ground motion underwater that would clarify the nature of ground shaking that offshore structures might experience; neither has the earthquake shaking of an offshore structure been recorded. Until this important information becomes available, the adequacy of the methods of analysis and design cannot be checked. The structural configurations of offshore platforms are quite different from those of onshore buildings, so experience cannot easily be transferred. The physical properties of platform structures and their foundations should therefore be studied.

Tsunamis

Tsunamis are long water waves generated by vertical displacements of the ocean bottom during an earthquake; such destructive waves can also be generated by underwater landslides, volcanic eruptions, and other forces. Although only a small fraction of earthquakes generate significant tsunamis, when a tsunami does strike a coast it can cause extensive destruction. This was demonstrated in the 1964 Alaska earthquake, in which the coastal cities of Kodiak, Seward, and Valdez were extensively damaged by the impact and run up of large waves. A tsunami can travel thousands of miles across the ocean and still be destructive, as demonstrated by the damage done to Crescent City, California, by the 1964 Alaska earthquake tsunami. Thus even events occurring across the ocean can lead to tsunami hazard. Damaging waves can also be generated in inland reservoirs, as happened during the 1959 Hebgen Lake, Montana, earthquake, in which the wave passed over the crest of the dam.

Recent research has developed methods for calculating the generation, propagation, and run up of tsunamis under simple geographic conditions and their effects on harbors. This has significantly improved the reliability of the tsunami warning system. However, the actual topography of the ocean bottom, of the continental shelf, and of the coastal shore is usually not simple, and these complications can strongly influence the run up of a tsunami. Further study is needed of this complex problem. In particular, studies should be focused on evaluating the impact of tsunamis on exposed coastal facilities in the United States.

Recommendations

1. Analytical and experimental studies should be made of the behavior of dams during earthquakes with the objectives of (a) making more reliable safety assessments and failure analyses of existing dams and (b) developing more realistic methods of analysis and design of dams to take into account their actual shapes and the properties of their foundations.
2. Seismic instrumentation should be installed on selected modern petroleum storage tanks to record their performance during earthquakes so that new methods of seismic design can be corroborated. Further studies should also be made of the seismic behavior and design of superlarge storage tanks.
3. Earthquake instrumentation should be installed on selected offshore drilling platforms in seismic regions to confirm the reliability of presently used methods of design and construction.
4. Studies to assess hazards should be made of those regions that might experience tsunamis in the future. These studies should consider the engineering features of tsunami generation and run up and the hydrodynamic forces exerted upon structures.

Social and Economic Aspects

In planning and preparing for protection of the public during earthquakes, social, economic, and political factors may be very important. For example, every city in the United States contains many buildings that would be very hazardous in the event of strong ground shaking, and many of these are in regions where strong earthquakes have occurred in the past. But efforts to deal with the problem of hazardous buildings in Los Angeles and in San Francisco have encountered complex social and economic issues. Because these buildings provide low-cost housing and low-cost commercial space, landlords are opposed to strengthening them unless they foresee a demand for upgraded accommodations, tenant groups are opposed because they expect an increase in rents, and senior citizen groups are opposed because they feel that the reduction in short-term hazard would not be worth the increased cost. Such programs to reduce hazards can also significantly affect a city's redevelopment program, its tax base, and so on. Planning and preparing for earthquakes and for earthquake relief measures raise similar problems. A basic question is, In view of the social, economic, and political considerations, what are the appropriate measures to be implemented?

Only since the 1964 Alaska earthquake has research been done on the foregoing aspects of mitigating earthquake hazards. In recent years city governments, state governments, and the federal government have become increasingly aware of the earthquake problem and the need to do something about it. Newspapers, magazines, and TV programs have devoted considerable attention to earthquakes and their hazards, and this has clearly increased public and governmental interest in the problem.

During the past decade earthquake prediction has received much attention from the news media and, therefore, from the public. News accounts of earthquake predictions in China, Japan, and the Soviet Union have often been sensationalized so as to be quite misleading, and in many cases the accounts have been based on incorrect reports. Even international earthquake predictions have been reported in newspapers, as when a Russian seismologist predicted a large earthquake in California, or when a U.S. scientist predicted a major earthquake in Peru. Recently, a U.S. National Earthquake Prediction Evaluation Council was formed whose function is to evaluate predictions and to give advice about their scientific validity. In China and Japan predictions of earthquakes, both real and rumored, have produced social unrest. In the United States a generally accepted earthquake prediction would clearly have serious impacts on financial institutions, insurance companies, local governments, and the public itself. It is not yet known how best to deal with the social implications of earthquake predictions.

When a destructive earthquake does occur, it is clearly advantageous if the cities affected have made plans to cope with the effects of earthquakes. Government agencies, relief organizations, and other concerned groups should be prepared to take appropriate actions without lengthy delay; individuals should also have an understanding of appropriate actions to take. In some highly seismic regions of the

United States, local government agencies are making plans and preparations, and the public is receiving advice. However, the study of the social science aspects of the earthquake problem is still in its infancy, and significant improvements can no doubt be made in the methods used to prepare for and respond to a destructive earthquake.

It would be very helpful for government planning if reliable, albeit approximate, analyses could be made of the impact of an earthquake on a city. For example, what would be the impact on Los Angeles if a magnitude 7 earthquake were to occur on the Newport-Inglewood fault? What would be the impact on Salt Lake City if a magnitude 7.5 earthquake were to occur on the Wasatch fault? What would be the impact on St. Louis or Memphis if there should be a repetition of the 1811-1812 earthquakes? Studies of this nature have been carried out in recent years, but they have reached widely differing conclusions as to the number of casualties and economic losses. The scanty data available on past earthquake damage in a form appropriate for extrapolating to future earthquakes make a reliable estimation of loss difficult. Studies of future destructive earthquakes should contain a component aimed at collecting data specifically for improving the estimation of loss.

The subject of earthquake insurance has been debated ever since the 1906 San Francisco earthquake. Insurance companies have technical reasons for not wanting to carry much earthquake insurance, and it is not clear that earthquake insurance for homeowners can be justified economically. A combined study by earthquake experts and insurance experts should take an in-depth look at this problem.

During recent years land use planning has received increasing attention in seismic regions. Planners recognize that some areas in a city may be much more hazardous than others because of proximity to a fault, hazard from landslides, danger of soft soils settling during earthquakes, hazard from tsunamis, etc. For example, state law in California now requires that special geological investigations be made of proposed building sites for schools to ensure that they have no special earthquake hazards. In general, however, land use planning for earthquakes has not progressed very far because of the many social, economic, and political issues involved.

The social science studies of the earthquake problem that have been made have increased knowledge and put the problem into sharper focus, but they are just beginning.

Recommendation

1. Studies should continue on aspects of the societal response to earthquakes and on the social aspects of earthquake preparations.

These studies should include analyses of the social costs and benefits involved in mitigating and in responding to earthquake disasters.

Postearthquake Investigations

Many of the most important aspects of destructive earthquakes cannot be studied in the laboratory. For example, it is not possible to model physically the earth's crust with its faults, strains, and generation of earthquakes; nor is it possible to test realistically such structures as buildings, bridges, and dams. Only during and immediately after an earthquake can these subjects be observed in action and studied. It is important therefore to think of the earthquake as a full-scale experiment, and preparations should be made to learn from an earthquake when it occurs.

Over the past decade postearthquake investigation of damaging earthquakes, emphasizing both engineering and geological factors, has contributed greatly to an increased understanding of earthquake hazards and to an implementation of corrective measures. For example, postearthquake studies of the 1971 San Fernando earthquake led directly to (1) major improvements in local building codes, (2) recognition by statute that hospitals deserve special considerations in seismic design, (3) major tightening and upgrading of dam inspection procedures, (4) new state laws regarding the placement of structures within active fault zones, (5) revised building standards for highway bridges, (6) renewed pressure to rehabilitate pre-1933 unreinforced masonry structures, (7) improved response procedures by police, fire, and other emergency forces, (8) accelerated studies of fault zones, emphasizing the establishment of earthquake recurrence intervals and degrees of activity, and (9) the installation of instruments and the recording of strong ground shaking and strong building vibrations, which provided the basis for an advance in earthquake engineering.

Much can be learned from the full-scale experiment presented by an earthquake. Moreover, the funds expended in preparing for and studying an event are minute compared with the actual cost of the experiment. For example, the cost of damage from the San Fernando earthquake was about $500 million (1971 dollars), whereas the cost of studying it was less than one tenth of one percent of that amount.

To learn from earthquakes it is important to make adequate preparations for learning. Extensive preparations are being made in Japan, where in 1923 the capital and largest city suffered the worst earthquake disaster in the country's history. The same sense of urgency is not evident in the United States, where the worst earthquake disaster occurred 3,000 miles from the capital in 1906. When an earthquake occurs, field studies must immediately be initiated to investigate the mechanism of the earthquake and the performance of structures and facilities. Research must then be carried out on the data collected from the earthquake. Since the occurrence usually has no forewarning, the expertise for studying the event must be mobilized, the effort must be coordinated, and these activities must be funded without delay. This has been difficult to accomplish for past earthquakes. The problem of how best to learn from earthquakes has not yet been solved; in particular, having funds immediately available for carrying out the necessary work both inside and outside the United States is a problem.

One of the difficulties in studying destructive earthquakes is that they occur relatively infrequently in a region. This, of course, is a problem that is not unique to the United States but that all countries with seismic hazards face. Because of this, it is desirable to view earthquake engineering as a world problem and to cooperate with other countries in studying earthquakes and sharing information. During the past decade many countries have developed expanded programs of earthquake engineering research and have installed networks of strong-motion instruments. Countries with which the United States exchanges such information include Japan, China, Yugoslavia, New Zealand, India, Turkey, Italy, Mexico, Peru, Chile, Taiwan, and others. World conferences on earthquake engineering are held at four-year intervals, with the next to be held in San Francisco in 1984. Among the shared information is data on earthquake generation, strong-motion accelerograms, recordings of structural vibrations, observations of damage to buildings, and descriptions of the performance of industrial facilities. Because building practices differ, probably the most important information shared among seismic countries comes from studies of earthquake generation and recordings of strong ground motions.

Because studies of earthquakes have only humanitarian motives and no political implications, there should be no real impediments to international cooperation. Such cooperation would seem to be particularly appropriate for U.S. aid programs for third world countries. The possibilities for cooperating and learning from earthquakes worldwide are illustrated in Table 2, which gives a selection of destructive earthquakes that have occurred outside the United States since 1960.

Postearthquake investigations of foreign earthquakes by American teams have provided important information in the past. For example, studies by American teams of damage to large petroleum tanks from the 1978 Miyagi-Ken-Oki, Japan, earthquake have contributed to improved design procedures in this country; postearthquake field studies of the 1980 El Asnam, Algeria, earthquake have provided a better understanding of the tectonic processes and damage associated with thrust faults, such as those present in much of the American

TABLE 2 A Selection of Significant Foreign Earthquakes Since 1960

Year	Date	Location	Mag.	Deaths	Remarks
1960	Feb. 29	Morocco; Agadir	5.7	12,000	One third of population of Agadir killed. Most of the city destroyed.
1960	May 22	Chile; Arauco Province	8.5	2,230	Tsunami caused 61 deaths in Hilo, Hawaii, and 120 deaths in Japan. Travel time of tsunami from Chile to Japan (11,000 miles) was 22 hours.
1962	Sep. 1	Northwestern Iran; Qazvin	7.3	12,200	
1963	July 26	Yugoslavia; Skopje	6.0	1,070	Many buildings damaged or collapsed.
1964	June 16	Japan; Niigata	7.5	26	Considerable liquefaction and subsidence caused much building damage. Large tsunami caused coastal flooding.
1965	Mar. 28	Chile (central)	7.5	600	Extensive damage.
1967	July 29	Venezuela; Caracas	6.5	266	Many buildings damaged. Several high-rise buildings collapsed.
1967	Dec. 11	India; Koyna Dam	6.4	177	Caused by filling of the reservoir. Village of Koyna Naga heavily damaged.
1968	Jan. 14	Sicily (western)	6.1	740	Seventeen earthquakes with magnitudes 4.1 to 6.1 from Jan. 14 to Feb. 6.
1968	May 16	Japan; Hachinohe (off the coast)	8.6	48	Known as the Tokachi-Oki earthquake. Damage to many buildings and port facilities from tsunami.
1968	Aug. 31	Iran (eastern); Khorasan Province	7.3	12,100	About 60,000 people homeless.
1970	Mar. 28	Turkey; Gediz	7.3	1,100	Many buildings collapsed.
1970	May 31	Peru; Chimbote	7.8	67,000	Greatest earthquake disaster in the Western Hemisphere. About 800,000 people homeless. Huge landslide on Mt. Huascarán buried 18,000 people in Ranrahirca and Yungay.

TABLE 2 A Selection of Significant Foreign Earthquakes Since 1960—(*Continued*)

Year	Date	Location	Mag.	Deaths	Remarks
1971	May 22	Turkey; Bingol	6.7	750	Many villages damaged.
1971	July 8	Chile; Illapel	7.5	83	Tsunami at Valparaiso.
1972	Apr. 10	Iran; Qir	7.1	5,400	City destroyed.
1972	Dec. 23	Nicaragua; Managua	6.2	5,000	Extensive building damage.
1973	Jan. 30	Mexico; Michoacán coast	7.5	56	Heavy damage.
1973	Feb. 6	China; Sichuan Province	7.9		Casualties and damage.
1973	Aug. 28	Mexico; northern Oaxaca	7.2	530	Many houses destroyed.
1974	May 11	China; Yunnan Province	7.1	20,000	
1974	Oct. 3	Peru; Lima	7.6	78	Extensive damage in Lima.
1975	Feb. 4	China; Liaoning Province; Haicheng	7.3	10,000	Earthquake was successfully predicted. Evacuations took place. Heavy damage, but many lives saved.
1976	Feb. 4	Guatemala	7.5	23,000	Extensive damage to adobe-type buildings. Numerous landslides. One fifth of the population homeless.
1976	May 6	Italy; Friuli region (near Gemona)	6.5	965	Extensive damage; many buildings destroyed.
1976	July 28	China; Hebei Province; Tangshan	7.8	243,000	Major industrial city totally destroyed. Four aftershocks on same day of magnitudes 6.5, 6.0, 7.1, and 6.0.
1976	Aug. 17	Philippine Islands; Moro Gulf	8.0	6,500	Many buildings damaged. Large tsunami.
1976	Nov. 24	Turkey (eastern)	7.3	5,000	Many buildings collapsed in the towns of Muradiye and Caldiran.
1977	Mar. 4	Romania; Vrancea region	7.2	1,570	Many buildings collapsed in Bucharest.
1978	June 12	Japan; Sendai	7.5	27	Some buildings damaged in this modern city.
1978	June 20	Greece; Thessaloniki	6.5	50	Much damage to buildings.
1978	Sep. 16	Iran (central); Tabas	7.7	15,000	In Tabas, 9,000 out of 13,000 killed.
1979	Mar. 14	Mexico; State of Guerrero	7.6	5	Many buildings damaged.
1979	Apr. 15	Yugoslavia; southern Montenegro	7.0	156	Near the Adriatic coast. Extensive damage.

TABLE 2 A Selection of Significant Foreign Earthquakes Since 1960—(*Continued*)

Year	Date	Location	Mag.	Deaths	Remarks
1980	Oct. 10	Algeria; El Asnam	7.3	5,000	Large fault scarps. Many buildings collapsed; 200,000 people homeless. El Asnam 60 percent destroyed.
1980	Nov. 23	Italy (southern)	7.0	3,100	Several large shocks. Great damage to homes built of stone masonry in Calabritto and nearby towns.
1981	Feb. 24	Greece (Gulf of Corinth)	6.6	18	Several buildings collapsed in Loutraki, northeast of Corinth. Minor damage in Athens. Many aftershocks.
1981	June 11	Iran (southeastern); near Kerman	6.9	3,000	Town of Gol Bagh severely damaged.
1981	July 28	Iran (southeastern); near Kerman	7.3	1,500	Town of Shahdad severely damaged; 50,000 people homeless.
1981	Sep. 12	Kashmir	6.1	212	Many houses damaged.

SOURCE: James M. Gere, *Earthquake Tables*, John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, Stanford, California, 1982.

This eight-story building in Central America collapsed like a deck of cards during moderately strong earthquake shaking. By studying earthquake failures in the United States and in foreign countries, engineers learn about structural weaknesses and how to improve seismic design.

west; and field studies of the great earthquake of 1960 in southern Chile (magnitude 8.5) enhanced the understanding of the regional tectonic framework for the remarkably similar great 1964 Alaska earthquake (magnitude 8.4).

To improve our understanding of earthquake hazards, it is essential that postearthquake investigations, including investigations of significant foreign earthquakes, continue to be encouraged and supported in a timely fashion so that critical evidence does not disappear, and it is essential that the investigations involve a wide spectrum of expertise.

Recommendation

1. Greater effort should be made to learn from earthquakes. This effort should include appropriate instrumentation for recording significant aspects of ground shaking and structural response, studies of instrument records obtained, analyses of building performance and damage, and investigations of earthquake generation. Particular attention should be paid to learning what improvements should be made in hazard assessment, earthquake zoning, seismic analysis and design of structures, social impact, and so on. This process should involve both prompt postearthquake investigations and in-depth follow-up studies.

Earthquake Engineering Education

An effective program of earthquake hazard mitigation requires research to produce information about earthquakes, their effects, and how to cope with them. In addition, however, the implementation of a program of earthquake hazards mitigation requires a body of educated engineers who understand the nature of the problem and know how to design structures and facilities that can withstand earthquake shaking.

During the past decade education in earthquake engineering has notably improved in the universities of the United States. The advanced nature of the subject requires that it be taught mainly at the graduate level, but undergraduate students now receive more introductory information than before on dynamics and structural vibrations in courses on mechanics and structures. This contact at an undergraduate level with the subject prepares students if they elect to study earthquake engineering later in their careers.

Postgraduate engineering education in the United States is facing serious problems because of (1) the difficulty of attracting good new staff members, (2) the difficulty of attracting a sufficient number of capable students, and (3) obsolete laboratory equipment for teaching and research. Postgraduate education in earthquake engineering faces all these problems even more severely because of the special conditions involved in an earthquake hazards reduction program.

Only a fraction of engineering students continue into graduate school. Thus the number of students who study earthquake engineering is small, and the number who proceed to the Ph.D. degree is much smaller. This problem of small numbers is exacerbated by the fact that approximately one half of the students studying earthquake engineering are from foreign countries with seismic regions, such as India, Taiwan, and the Middle East, and many of these students return to their countries of origin. Industry has a large demand for graduates that have studied earthquake engineering and an even larger demand for students knowledgeable in structural dynamics and digital computations, and the high salaries and other perquisites industry offers are effectively enrolling graduates and draining personnel from university faculties. These personnel shortages are expected to continue and, possibly, to become more critical. Incentive programs, with continuity of funding, are urgently needed that will encourage able U.S. students to attend graduate school and specialize in earthquake engineering and related subjects.

An important element of education in earthquake engineering is the publication of research reports, papers in technical journals, and proceedings of conferences. This is how research results are brought to the attention of the earthquake engineering community. During the past decade the number of such publications has increased substantially. Two international journals of earthquake engineering are now published, and papers on earthquake engineering appear in the publications of the American Society of Civil Engineers, the Seismological Society of America, and the American Society of Mechanical Engineers. There is now a need for scholarly syntheses to be made of published research results on important topics in earthquake engineering. Such syntheses would be of great learning value to those who want to study these topics. A number of books on earthquake engineering have been published, along with monographs on special aspects of the subject (the Earthquake Engineering Research Institute is now publishing a series of monographs on earthquake engineering). Most of the foregoing publications are of interest mainly to research workers and graduate students and are less suitable for practicing engineers. Books and articles on specialized topics in earthquake engineering are needed in which the author has presented the relevant results from research in a form suitable for practical application and in a way easily understood by practicing earthquake engineers.

The majority of those now responsible for the practice of earthquake engineering did not have courses in the subject during their university education, and this situation will apparently not change substantially in the foreseeable future. There must therefore be a program of continuing education consisting of concentrated short courses, seminars, special lectures, and so on. During recent years activity in continuing education has increased, but this has served mainly middle management personnel. There is a need for more effective continuing education for younger engineers. A fellowship program that would allow engineers to return to universities full time for one or more academic terms would be desirable.

Specialized workshops and seminars have in recent years effectively educated engineers, architects, and planners in various aspects of seismic safety. These workshops typically bring together 15 to 30 people for one or two days to concentrate on a specific aspect of the subject and then draw up a position statement. Such workshops have been very effective, but unfortunately they reach only a relatively small number of people, who are expected to disseminate information to their colleagues. Organized by the Earthquake Engineering Research Institute (EERI), seminars in major cities in the United States have had from 50 to 500 people in the audience listening to lectures on specialized topics in earthquake engineering. Technical meetings of these types play an important role in disseminating the results of research and in educating the profession; they should certainly be continued.

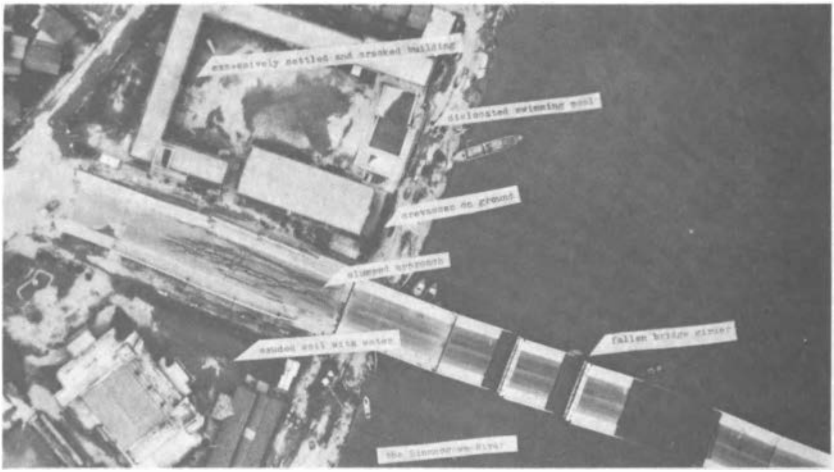
A number of societies and organizations play important roles in earthquake engineering. These include the Universities Council for Earthquake Engineering Research (UCEER), the Earthquake Engineering Research Institute, the Seismological Society of America (SSA), the Applied Technology Council (ATC), the Structural Engineers Association of California (SEAOC), the American Concrete Institue (ACI), the American Society of Civil Engineers (ASCE), the American Society of Mechanical Engineers (ASME), and the International Association for Earthquake Engineering (IAEE). These organizations hold conferences, organize workshops and seminars, publish technical papers and monographs, and in general play important roles in disseminating information in earthquake engineering. In addition, the National Information Service in Earthquake Engineering (NISEE) maintains two data centers that collect books, reports, technical papers, journals, accelerograms, computer programs, and other resources and make these available to researchers, engineers, public officials, the news media, and others. There is also an *Abstract Journal in Earthquake Engineering*, which provides a comprehensive collection of abstracts and citations of world literature in earthquake engineering.

Recommendations

1. The number of U.S. graduate students studying earthquake engineering should be increased by means of appropriate incentives to satisfy the needs for research workers, university faculty members, and advanced engineering consultants for industry.
2. Earthquake engineering research and teaching laboratories at universities should be modernized and upgraded.
3. A program of continuing education for practicing engineers, government officials, and others concerned with the earthquake problem should be maintained. This program should seek to create an awareness of the earthquake problem and to disseminate the results of earthquake engineering research through the publication of technical papers, monographs, specialized books, and other resources.

Research in Japan

Japan and the United States are two large industrialized countries with serious earthquake problems, and both have conducted programs in earthquake engineering research during the past decade. Examining the program of earthquake hazards mitigation in Japan and comparing it with that in the United States can therefore be very informative. Both countries have suffered similar earthquake-fire disasters in this century: the 1906 San Francisco earthquake and the 1923 Tokyo



This aerial view shows a fallen bridge in Japan. Japan is another large industrialized country with a serious earthquake problem, so a comparison of the earthquake research program in Japan with that in the United States can be very informative.

earthquake. Both countries now expect another large earthquake to occur in the not-too-distant future. Because many of Japan's 112 million inhabitants are concentrated in large cities, their exposure to seismic hazards is large.

Although both countries face similar earthquake problems and have been carrying out research aimed at solving these problems, it is difficult to compare their programs of earthquake hazard mitigation because of certain differences in approach. Research on earthquakes is carried out at universities in Japan, just as it is in the United States. However, government agencies do more research in Japan than do government agencies in the United States. Many large industrial corporations in Japan also have laboratories that carry out earthquake engineering research, and this represents a much larger effort than that done by U.S. corporations. The six largest engineering construction companies in Japan maintain large research laboratories with as many as 500 employees, and applied research in earthquake engineering is an important part of their activities.*

Japan has a vigorous earthquake prediction and warning program. At present much attention is being focused on the Tokai region, west of Tokyo, in which a large earthquake is expected. Elaborate plans have been formulated to warn the public of a predicted earthquake, in which the Prime Minister receives information about the prediction and, in consultation with the Cabinet, decides whether to issue an earthquake warning statement. The consensus of earthquake scientists in Japan is that the Tokai warning system may issue a false alarm, but that it is not likely to miss the imminent occurrence of a big event.

---

*It was not possible, within the time frame and funding level of this project, to make a detailed evaluation of earthquake engineering research in Japan, though it is desirable that it be done. If such a follow-up study is made, it would be better to describe the effort in terms of manpower rather than dollars or yen. The approximate number of man-years of research personnel and support personnel should be given. Experimental facilities should be described, and the estimated capital costs and operating costs in dollars should be given. Examples of research that the Japanese program is accomplishing should be described and compared with the U.S. research program. The long-term advantages and disadvantages of the Japanese program should be discussed. The U.S. research program should also be described in terms of manpower and experimental facilities. It would also be informative to develop a similar description of the Chinese earthquake engineering research program, which is also larger than the U.S. program. The 1982 Chinese program included approximately 2,500 men (one third research personnel and two thirds support personnel) and more experimental facilities than the U.S. program. Clearly, the 1923 Tokyo, Japan, and the 1976 Tangshan, China, earthquake disasters have provided strong motivation for developing vigorous programs of research in these two countries. The next earthquake disaster in the United States can also be expected to motivate the development of a strong research program, and preparations should be made to put it into effect.

The instrumentation program for recording strong ground shaking in Japan is similar to that in the United States. However, government agencies have installed a larger fraction of the instruments in Japan than have government agencies in the United States. The Port and Harbour Research Institute, the Public Works Research Institute, and the Tokyo Metropolitan Government operate over 500 stong-motion instruments. Other governmental groups, universities, private companies, and building owners operate many additional strong-motion instruments.

Earthquake engineering research in Japan has a much stronger component of experimental research than is the case in the United States. Many very impressive experimental research facilities have been, or are being, constructed in Japan. For example, the new National Research Center for Disaster Prevention in Tsukuba Science City has a 15-m by 15-m shaking table with a capacity of 500 tons that is capable of planar motion. The Building Research Institute in Tsukuba has a large structural laboratory with two test floors and a common reaction wall that cost about $8 million. In addition, it has another structural laboratory with large static test machines and a 4-m by 4-m shaking table. The Public Works Research Institute has constructed facilities for earthquake engineering research in Tsukuba at a cost of about $20 million. A 6-m by 8-m shaking table has a capacity of 100 tons, and work is now under way to add four smaller shaking tables along an axis so that independent earthquake excitations can be applied to the piers of models of long-span bridges. The Institute has also recently completed a 4-m by 4-m earthquake simulator for dams and a laboratory with a strong-room test pit for testing the nonlinear characteristics of structures and structure-soil specimens. The test pit is 20 m by 15 m, and the maximum alternating force is 125 tons at a speed of 1 m/s. The Nuclear Power Engineering Test Center in Tadotsu, Shikoku, is now completing construction of a high-performance earthquake shaking table facility at a cost of about $200 million. The table is 15 m by 15 m with a capacity of 1,000 tons at 1.84 g horizontally and 0.92 g vertically. These experimental facilities will provide the Japanese with engineering data of great value, which in general will not be available to U.S. research workers. Also, it is felt that cooperative Japan-U.S. experimental research carried out in Japan is not a productive way to provide data to U.S. research workers.

A very large program of earthquake preparedness is being carried out in Japan. The basic policy is formulated in the 1978 Large-Scale Earthquake Counter Measures Act, which outlines the basic steps required of the national, prefectural, and local governments once an area, such as the Tokai region, has been designated an "intensified area." These steps include the "intensified plan," which deals with medium- to long-term issues such as the installation of earthquake instruments; the identification of high-damage areas; strengthening of buildings, lifelines, and other facilities; public education; and the establishment of public announcement procedures. In addition, a short-term plan deals with such issues as notification, evacuation, care and handling of refugees, medical treatment, traffic control, and repairs. The act also deals with emergency powers, financial assistance to effectuate the plans, promotion of scientific research, and other issues.

In accordance with the act the national government in 1980 issued its Basic Plan of Earthquake Disaster Prevention for Areas Under Intensified Measures Against Earthquake Disaster, in preparation for the Tokai earthquake. This is a policy statement that requires ministries, agencies, and local governments to prepare detailed plans and undertake activities to prepare for an earthquake. For the anticipated Tokai earthquake, approximately $1.5 billion is being spent during the period 1980-1984. The Tokyo city government spent some $5 billion for disaster prevention in 1972-1977 and plans to spend about $7 billion for the period 1978-1983. Osaka, the third largest city in Japan, is spending about $200 million a year over the 1978-1987 period for disaster mitigation (divided about equally between flood and earthquake mitigation).

A difficulty was encountered in trying to compare funding for earthquake research in Japan with that in the United States. The figures in Japan do not include salaries, overhead, or other indirect costs, whereas the figures in the United States do include these costs, which for most projects represent at least 75 percent of the budget. Nevertheless, the earthquake engineering research effort in Japan appears to be approximately four or five times greater than that in the United States, excluding the costly large experimental research facilities in Japan. The research effort related to earthquake prediction seems also to be approximately four times greater in Japan than in the United States.

In addition, recent visits to the People's Republic of China have shown that the government is building up its earthquake engineering research, with the effort already greater than that in the United States. For example, in Harbin a staff of 550 is devoted entirely to earthquake engineering research; the Academy of Building Research in Beijing, with a staff of 1,200, has very large and impressive earthquake engineering research facilities; Tsinghua University in Beijing, Tongji University in Shanghai, and Dalian Polytechnical University in Dalian have major programs of earthquake engineering research that include impressive laboratory facilities; and a number of government ministries maintain large earthquake engineering research laboratories. The total effort is estimated to be three to four times that of the United States.

In conclusion, the United States has fallen behind Japan (and China) in the size of its earthquake engineering research effort. This is particularly the case for experimental research facilities. This is cause for concern, because the experimental facilities produce the basic data needed for progress in earthquake engineering research. Without progress in earthquake engineering research, the practice of earthquake engineering in the United States will become a second-class operation.

Recommendation

1. A much stronger experimental earthquake engineering research program should be implemented in the United States. An in-depth examination should be made of the present program in the United States, and this should be compared with the program in Japan. The needs for a vigorous U.S. program should be identified, including small- and medium-scale experimental facilities as well as large-scale facilities. This study of the U.S. and Japan experimental research programs should be undertaken immediately, and suitable reports with recommendations should be prepared and acted upon.

General Conclusions and Funding Recommendations

Earthquake disasters, which can cause thousands of deaths and billions of dollars of destruction, result from the failure of buildings and facilities that are not properly designed to resist strong ground shaking and are therefore weak relative to earthquake loads. Cities in the United States, as well as in the rest of the world, are vulnerable to disaster should strong shaking occur. Cities in highly seismic regions of the United States are less vulnerable because of earthquake requirements in building codes, but they contain many buildings that were constructed before these requirements were adopted, and these structures could collapse in the event of a strong earthquake. Even buildings constructed according to earlier seismic codes can be susceptible to severe damage and collapse, as earthquakes in Alaska in 1964, San Fernando in 1971, Santa Rosa in 1974, Imperial Valley in 1979, and elsewhere have demonstrated. Special structures, public utilities, industrial facilities, and other structures not governed by the seismic requirements of building codes are similarly vulnerable.

The long-term solution of the earthquake problem is to replace the vulnerable structures by appropriately designed buildings that will not suffer undue damage when an earthquake occurs. This requires research to provide the necessary knowledge and to develop correct and practical methods of design, a body of educated earthquake engineers with the expertise to carry out the required design, and a high level of earthquake engineering over the years. If the required knowledge had been available in 1882 and the necessary engineering expertise had existed, and if the decision had been made that structures and systems in all cities should be properly designed, there would not now be an earthquake problem. The long-term solution of the earthquake problem is the objective of earthquake engineering, even though practical difficulties may obstruct and delay that solution. Unfortunately, destructive earthquakes are certain to occur before the long-term solution is achieved, so short-term problems must also be faced.

Federal, state, and city governments must recognize that the earthquake problem will continue to exist until man-made works are upgraded and no longer vulnerable. In addition, they should be aware that large destructive earthquakes will occur before the long-term solution is reached, and special preparations must be made to mitigate the earthquake hazard as much as is practically possible.

This conclusion can be put into focus by comparing the U.S. effort with that of Japan and China. The earthquake engineering research program in Japan is four or five times greater than that in the United States, even excluding the large costly experimental facilities in Japan. China also has a program of earthquake engineering research that is three or four times larger than that of the United States. The short-term level of effort in Japan to prepare for coming earthquakes is also very much greater than that in the United States. Of course, the fact that Japan and China both are implementing large earthquake hazard reduction programs does not of itself mean they should necessarily be emulated by the United States. However, the existence of these large programs alerted the Committee to examine them and to compare them with the U.S. program. The Committee was greatly impressed by the potential of the Japanese and Chinese programs, particularly in experimental research, and concluded that the present level of the U.S. program is inadequate to accomplish what the Japanese and Chinese programs will accomplish. While urging that the United States' program be expanded, the Committee recognizes that its future quality cannot be ensured by trying to match foreign programs dollar for dollar or person by person. Rather the Committee feels that an increase in earthquake engineering research funding should be closely tied to increased educational efforts in this field.

In view of the short-term and long-term earthquake problems facing the United States, the present level of earthquake engineering research in the United States should be increased. Funding should be increased to $35 million per year now with a gradual increase to about $50 million per year in 10 years. These levels consist of increases in the range of 50 to 150 percent over the present funding levels and represent a feasible program of earthquake engineering research. This program would have as its research components (1) the assessment of earthquake hazard, (2) recording and analyzing strong earthquake ground motions, (3) soil mechanics and earth structures, (4) analytical and experimental structural dynamics, (5) the seismic interaction of structures and fluids, (6) the social impact of earthquakes, (7) architecture and planning, (8) postearthquake investigations, (9) earthquake engineering education, (10) an expanded program of experimental research, (11) upgrading of experimental facilities at universities, and (12) an upgrading of methods of seismic design.

The program of research represented by the funding levels recommended above can provide data that would lead to safer and more economical design of structures and facilities. However, the Committee would be remiss if it did not emphasize that these recommended levels of funding for research will not solve the earthquake problem in the foreseeable future. It will improve earthquake safety but will not eliminate earthquake risk. The problem is too large for this to be the solution. Construction in the United States takes place at a rate of about $230 billion per year, or about $5 trillion in 20 years. A problem of this magnitude requires a correspondingly strong earthquake hazard reduction program if it is to be solved in the next 100 years. The earthquake engineering research in Japan is four or five times greater than that in the United States, even excluding the large costly experimental facilities in Japan. China also has a program of earthquake engineering research that is three to four times larger than that of the United States. Moreover, the short-term level of effort in Japan to prepare for coming earthquakes is very much greater than in the United States.

It is the Committee's judgment that much more effort should be applied in the United States toward reducing earthquake risk. The Committee recommends levels of effort represented by the funding shown in Table 3 for earthquake engineering hazard mitigation. This recommendation is made from a broad view of earthquake engineering. In particular, it includes funds for a strong national program in large-scale testing and experimental facilities. It should be noted that the information developed by earthquake engineering research can also be used in the fields of wind engineering and blast engineering as well as to upgrade ordinary engineering and construction.

Although the recommended funding is much larger than the present U.S. program, it is perhaps on the small side for a program that seeks both short-term and long-term solutions to the earthquake problem. However, because the accumulated investments in buildings and facilities amount to trillions of dollars, and because these investments are now being added to in areas subject to moderate and major

TABLE 3 Recommended Funding for Categories of Future Earthquake Engineering Hazard Mitigation (in millions of 1982 dollars)

Year	Basic Research and Education	Large-Scale Testing and Experimental Facilities	Seismic Instrumentation, Data Analysis, and Hazard Assessment	Code Development, Ancillary Testing, and Continuing Education	Preparing for Earthquakes
1984	25	28	12	8	17
1985	28	40	18	10	24
1986	32	55	24	12	32
1987	38	65	32	12	40
1988	45	70	32	14	48
1989	52	65	36	14	48
1990	56	55	36	12	45
1991	53	50	32	10	45
1992	50	45	28	10	40
1993	50	45	28	10	40

earthquakes at a rate of approximately $180 billion per year, the potential for disaster is of alarming proportions.

The constituents of the categories listed in the Table 3 are as follows:

Basic research and education include university research by faculty members, graduate students, and postdoctoral fellows, education of future research workers and faculty members through the Ph.D. degree, education of future design engineers, planners, and other professionals through the B.S. and M.S. degrees, upgrading of research laboratories with modern equipment and instrumentation, and postearthquake investigations.

Large-scale testing and experimental facilities include instrumentation and equipment for testing and recording full-scale structures in the field (including earthquake motions), experimental facilities for testing large-scale models of structures, full-scale structural components, and large-scale soil samples, and large testing centers.

Seismic instrumentation, data analysis, and hazard assessment include strong-motion instrument networks and arrays, the processing and analyzing of seismic data, instrument development, dissemination of data, and hazard assessment.

Development of codes, ancillary testing, and continuing education include applied testing and research for design and code development, development of building codes and specialized codes, and continuing education of practicing engineers, planners, and architects.

Preparing for earthquakes includes studies and programs of reducing the hazard of existing weak buildings, strengthening deficient structures and systems, preparing state and local government agencies to cope with earthquakes, and educating the public.

The Committee strongly recommends that the federal government recognize the magnitude of the national earthquake hazard and undertake a long-term program to mitigate it. In addition, the federal government should take steps to prepare for the disastrous earthquakes that can be expected in the next several decades.

2

Applications of Past Research

Thirty years ago earthquake engineering was in its infancy. Only in more recent years, with the development of an active program of research, has the subject come to maturity. An important stimulus to the development of earthquake engineering research has been an urgent need for information by the designers of critical high-technology projects, such as thermal and nuclear power plants, major dams, high-rise buildings, offshore structures, liquefied natural gas (LNG) facilities, oil and gas pipelines, and sensitive industrial equipment. But the information developed by earthquake engineering research has been applied in many directions, as government officials, industrial corporations, practicing engineers, and even the public have come to realize the importance of preparing for earthquakes. In the United States, and in most other seismic regions of the world, increases in population and industrialization have generated a greater exposure to earthquakes and have thus increased earthquake risk. For example, 10 times as many people now live in the San Francisco metropolitan area as in 1906, and the public utilities, industrial facilities, and other systems are vastly greater now. Fortunately, most of the man-made structures in San Francisco are now much more resistant to earthquakes than in 1906, mainly through the application of the results of research.

The designs of nuclear power plants and transcontinental pipelines are good examples of how earthquake engineering research was able to satisfy an urgent need for information. Safety is an overriding concern in designing such critical facilities, much more so than for ordinary buildings. The ability to resist earthquake forces was therefore given special attention in their designs, not only in the highly seismic regions of the country but also in the remainder of the country, where earthquake hazard is much less. If a structure is to be designed for California or southern Alaska, regions of high seismicity, it is obvious that moderate to great earthquakes may occur and that the site can expect to experience strong ground shaking. On the other hand, around such regions as New Madrid, Missouri, and Charleston, South Carolina, where major to great earthquakes have occurred in the past but are very infrequent, the seismic hazard is not so clear. In regions of the country that have very low historical seismicity, the site of a structure

The 4-ft-diameter trans-Alaska oil pipeline traverses a region where large earthquakes occur, so the line was designed to resist ground shaking without jeopardizing the integrity of the pipe. This view shows the pipeline where it crosses the Denali fault. The special seismic design enables the pipeline to accommodate 20 ft of lateral fault displacement without interfering with the flow of oil.

will probably not experience strong earthquake ground shaking, but the possibility cannot be ruled out.

When designing a critical facility such as a nuclear power plant or a pipeline, it is therefore of great importance to assess realistically the likelihood of earthquake ground shaking in the future, particularly the strongest ground shaking that might occur. New methods of assessing earthquake hazard have thus been of great value in the safe design of these critical facilities. An important part of assessing seismic hazard is to specify the ground shaking to be considered in the design. The instrumental recordings of strong earthquake ground shaking in the western United States provided a data base for establishing such ground motions. Were this data base not available, the seismic design of critical facilities would have been seriously inhibited. Although originally developed in the United States, the foregoing methods of hazard assessment are now used in all other parts of the world for the seismic design of major facilities.

The seismic design of critical high-technology projects is based on the free-field ground shaking that the assessment of seismic hazard has specified. Detailed dynamic structural analyses are then made to determine the vibratory motions that this ground shaking would generate in the different parts of the structure and the dynamic stresses and strains that the structure must resist. During an earthquake massive structures interact with the surrounding ground, and this soil-structure interaction significantly influences the response of the structure itself. The vibratory motions of the structure in turn affect the equipment attached to various parts of the structure. Research on soil-structure interaction and on the dynamic response of complicated structural systems provided information that has been essential to the analysis and design of these systems. The highly developed methods of seismic analysis now used in the design of complicated structural systems were made available only through the results of relevant research.

These complex vibrational systems, composed of the structure, the surrounding ground, internal equipment, piping systems, piping connections between adjacent structures, and so on, are being studied further. Some of the more important topics are the interaction of the structure with impinging seismic waves, energy losses into the surrounding ground, the development of reliable, simplified methods to analyze complex systems dynamically, the resistance of construction materials to transient stresses and strains of high amplitude, and the motions and strains developed in the structure and equipment during actual earthquakes. The earthquake problems of critical facilities differ from the earthquake problems of ordinary structures, just as the level of design of an airplane differs from that of an automobile. Research into the problems of these facilities does not therefore necessarily apply to the design of ordinary structures, and vice versa.

When an earthquake occurs, everything connected to the ground directly or indirectly will experience motions and stresses and must be designed to resist these to avoid damage or failure. There are also many differences in seismic behaviors and in the knowledge needed to cope successfully with earthquake forces. Thus the scope of earthquake engineering is extremely broad. For example, the seismic design of a high-rise building requires quite different information than does the design of a single-family dwelling; the seismic design of a bridge is quite different from the seismic design of a dam; and the seismic design of electric power equipment is quite different from that of offshore drilling platforms. In the early days the earthquake problem was thought to be mainly one of designing ordinary buildings and dwellings to resist ground shaking. Now it is clear that public safety and welfare also depend on many special structures, industrial processes, urban lifelines, communication systems, operations of government agencies, and so on. As the populations of urban centers continue to increase and as the industrialization of our economy progresses, it will become increasingly important to cope with the earthquake problem.

Facilities Benefiting from Research

The results of earthquake engineering research form the bases for the safer designs of buildings; emergency, essential, and critical facilities; commercial, financial, and industrial facilities; and government facilities and operations. These categories can be subdivided further as follows:

1. Dwellings, institutional buildings, and public structures
   - Single and multifamily residences
   - School buildings
   - Hotels and motels
   - Low-rise and high-rise office buildings
   - Auditoriums, theaters, and stadiums
   - Airports, bus stations, and ports
2. Emergency facilities
   - Hospitals
   - Fire and police stations
   - Emergency operations centers
3. Essential facilities (lifelines)
   - Water and sewage
   - Energy (gas, electricity, fuel)
   - Communications (telephone, telegraph, radio, television, emergency systems)
4. Critical facilities
   - Thermal and nuclear power plants
   - Petroleum facilities (refineries, oil and gas pipelines, offshore platforms, petroleum storage tanks, liquefied natural gas storage tanks)
   - Chemical and biological facilities
   - Dams (water supply, flood control, and power generation)
5. Commercial, financial, and industrial facilities
   - Retail and wholesale establishments
   - Financial centers (banking, savings and loan, insurance)
   - Manufacturing plants
   - High-technology industrial plants
6. Government facilities and operations
   - Military airports
   - Naval installations
   - Army facilities
   - Government communications systems

The foregoing list is not complete, since it is intended to show only the scope of the earthquake problem and the many ways that earthquake engineering research can be applied. The following sections discuss some of these applications to show the importance of the problem and the needs for future research.

Dwellings, Institutional Buildings, and Public Structures

Most people work and live in ordinary buildings, and research and observations of their performance during past earthquakes have greatly increased the resistance of these structures to earthquakes. The seismic requirements of building codes, which govern the design of these structures, have been greatly improved in the last decade. Thus, if designed according to the new requirements, the types of structures that were badly damaged in past earthquakes will perform much better in future earthquakes. High-rise office buildings and public structures

The gridwork of beams and columns in these high-rise buildings provides the strength to resist earthquake forces. An earthquake hazard assessment was made for this project, and design earthquakes were specified. A digital computer analysis simulated the vibrations of the buildings under ground shaking produced by a magnitude 8 earthquake originating 35 miles from the site.

now being designed and constructed also have reduced seismic risk, because of an improved understanding of the seismic hazard, a better knowledge of earthquake ground shaking, a greatly enhanced capability of making structural analyses, and a better understanding of the physical characteristics of building materials.

Housing construction has also benefited from the results of earthquake engineering research. Improvements in seismic design, in the quality of materials, and in construction procedures are now being incorporated into single-family residences through building codes and requirements of the Federal Housing Administration of the Department of Housing and Urban Development (HUD). Guidelines for appropriate arrangements of earthquake-resisting elements and better connections between parts of the structure are presented in the HUD report *Methodology for Seismic Design of Single Family Dwellings*.

The proof that newer buildings can better resist earthquakes comes when an earthquake strongly shakes a city and the performance of modern buildings is compared with that of older buildings. The Long Beach earthquake of March 10, 1933, was generated on the Newport-Inglewood fault that passes through the city. Many dwellings were damaged, many commercial buildings collapsed in whole or in part, and many school buildings were severely damaged and would have caused deaths and injuries had the earthquake occurred earlier in the afternoon, when the schools were in session. Since then, no comparable event has occurred in the United States in which a fault passing through the center of a large city has generated a sizable earthquake, but numerous earthquakes have strongly shaken modern structures. Recent earthquakes in California have demonstrated that the resistance of single-family dwellings to earthquakes has been much improved, as has the performance of ordinary commercial buildings. In particular, modern school buildings in California have withstood ground shaking of an intensity equal to that in the 1933 Long Beach earthquake without sustaining significant damage because of the requirements of the Field Act, which came into force as a result of the severe damage to school buildings in that earthquake. The seismic design of common commercial and institutional building types has also been much assisted by the knowledge provided by accelerographs placed in the basements and upper parts of buildings and by the records obtained during earthquakes, notably San Fernando in 1971. However, since motions of strongly vibrating buildings have been recorded only during a few earthquakes, many recordings are still needed of buildings shaken so strongly that they are on the verge of damage or collapse.

The ability of structures to resist earthquake motions strongly depends on the physical properties of their materials of construction. Over the years an increased understanding of the capability of most structural materials to withstand dynamic earthquake stresses has developed, and the properties of the materials themselves have been improved. Better and more uniform concrete can now be produced because of improvements in the manufacture of cement, the production of concrete aggregates, and the procedures for mixing, placing, and curing concrete. Since concrete is used so widely as a building material, these improvements have had a significant effect on the strength and durability of structures. The construction of high-rise buildings has also benefited from improved procedures for rolling structural shapes in heavy steel without adverse side effects such as laminar tearing and from the development of steels that can be welded more easily.

Emergency Facilities

In the event of a destructive earthquake, it is of great importance that emergency facilities be in a functioning condition following the earthquake. The event should not put local government headquarters, fire and police facilities, disaster mitigation and communication centers, and hospitals out of operation. Unfortunately, in many past earthquakes emergency facilities have been put out of operation. In the 1906 San Francisco earthquake the fire department could not operate because of a lack of water; the 1933 Long Beach earthquake damaged the headquarters building of the fire department and knocked out the emergency communications system; the 1964 Alaska earthquake disabled the entire communications system in Anchorage and made hospitals unusable; the 1971 San Fernando earthquake put all five hospitals in that region out of operation.

During the past decade progress has been made in improving the resistance of some emergency facilities to earthquakes. The California State legislature passed an act requiring that all new hospitals be designed to be functional following a strong earthquake; the Veterans Administration has had its hospitals analyzed and strengthened to be safe during earthquakes; and a number of city administrations are examining the earthquake safety of their emergency facilities. The seismic design requirements for such facilities often incorporate state-of-the-art analysis and design, not only for the structure but also for equipment, systems, and components required for proper functioning. Disruption during past earthquakes has demonstrated a need for emergency operations centers where essential communication systems are centralized, and a number of governmental entities have established such centers in new facilities. However, even though progress has been made in improving the earthquake safety of emergency facilities, much remains to be done on this important earthquake problem.

This parking structure collapsed on ambulances during the 1971 San Fernando, California, earthquake. Five hospitals were in the region of strong shaking, and all were put out of operation by the earthquake, just when hospitals were most needed. California state law now requires hospitals to be designed to be functional after a strong earthquake. The methods of hazard assessment and seismic design employed for hospitals are now based on earthquake engineering research carried out during the past decade or so.

Essential Facilities

Past earthquakes have frequently damaged essential (lifeline) facilities. For example, in the region it shook most strongly, the 1971 San Fernando earthquake interrupted the water supply system and the sewage system, put the telephone system out of operation for a month, disabled the electric power distribution system, put the gas distribution system to homes out of operation, and caused a number of freeway overpass bridges to collapse. Disasters in urban areas can be particularly serious if, in addition to failures of buildings, the network of essential facilities that serve the community is substantially disrupted. Energy, transportation, communication systems, and water facilities are the lifelines of the community. It is important after an earthquake that lifeline facilities continue to perform, or that they at least can be easily repaired so that a community can quickly resume normal activity. Sometimes the loss of a lifeline facility, such as the failure of the telephone system to communicate emergency messages, or the failure of the water system to fight fires, can create secondary losses that are greater than the primary losses caused by the earthquake itself.

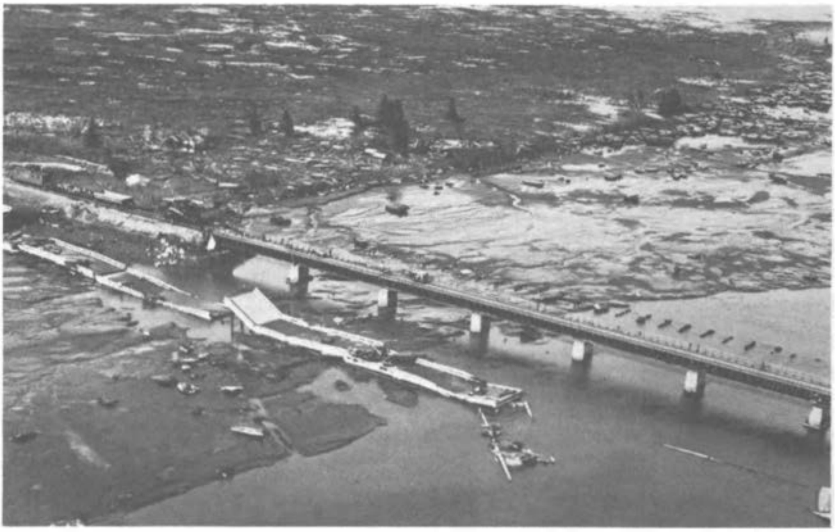
Furthermore, the earthquake problem of lifelines is complicated by the fact that engineering, governmental, and social aspects are all involved.

In recent years the effects of earthquake on lifelines have become a formal part of research. In the 1970s the American Society of Civil Engineers (ASCE) established the Technical Council on Lifeline Earthquake Engineering (TCLEE), a multidisciplinary group that through technical publications, conferences, and seminars could develop and exchange information on the earthquake engineering of lifelines. At present, ASCE-TCLEE committees are preparing technical advisory notes on the seismic design of lifeline facilities. The earthquakes in San Fernando in 1971, Miyagi-Ken-Oki, Japan, in 1978, El Asnam, Algeria, in 1980, and Campania-Basilicata, Italy, in 1980 provided many examples of lifeline failures during earthquakes that greatly aggravated the impact on the population. The lessons learned from these earthquakes will be of great value for future design and construction. However, even though research has improved our understanding of how essential facilities perform during earthquakes, the development of necessary knowledge has just begun.

In several states strong-motion recording instruments have been installed on lifeline facilities to monitor their performance during earthquakes and to evaluate seismic design criteria. During the 1979 Imperial Valley, California, earthquake, such an instrumented freeway overpass bridge was in the region of very strong shaking and produced an unusually complete and valuable set of recordings. Nonseismic vibration measurements have been made on a number of large bridges—for example, the Golden Gate Bridge in San Francisco—from which dynamic analyses have been made to throw light on their behavior during earthquakes. In recent years research has also developed methods of seismic analysis and design for liquid storage tanks and networks of underground water, sewer, and gas pipelines.

In 1969 the Federal Highway Administration (FHWA) initiated studies on the effects of earthquakes and wind on highway bridges, which were subsequently expanded to include tunnels and highways after the 1971 San Fernando earthquake. A recent project of the Applied Technology Council (ATC) resulted in the *Seismic Design Guidelines for Highway Bridges*, which the Bridge Committee of the American Association of State Highway and Transportation Officials is now considering for adoption. The California Department of Transportation and the FHWA have established guidelines to strengthen existing bridges using seismic retrofit methods, and most of the freeway overpass bridges in California have now been so strengthened.

The Bell Telephone Laboratories have developed new standards for the design and construction of telephone switch gear to ensure



This highway bridge collapsed but the adjacent railway bridge remained standing during the 1964 Alaska earthquake, demonstrating that the seismic performance of a structure depends on the engineering design.

satisfactory performance during earthquakes. The engineering problems of telephone communications are perhaps more easily solved than are the social problems. For example, during the San Fernando earthquake the Bell Telephone System remained operative, but for many hours afterward incoming phone calls saturated both the local and the long distance systems, making the emergency service of the systems ineffective.

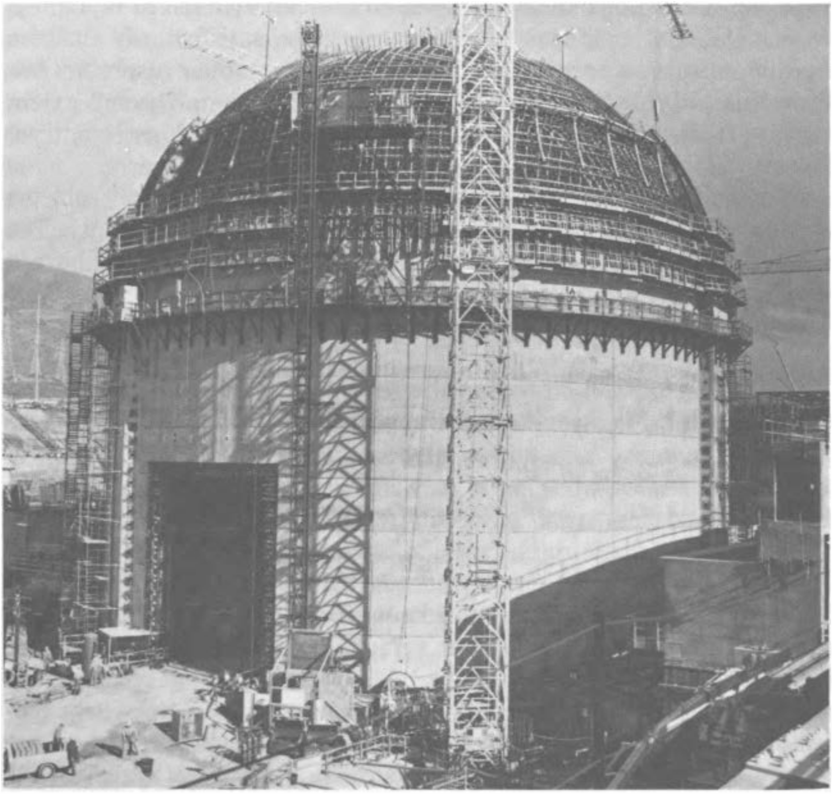
The past decade has brought both research and development in the seismic design of electric power distribution systems. Concerned power companies have drawn up seismic design criteria for electric power systems and equipment. Inexpensive methods to improve the seismic response of power systems have been identified, and information about them has been disseminated.

There is a continuing need for research on the actual performance of lifelines during earthquakes, on improved procedures of design for new lifeline facilities, and on techniques for upgrading the many existing essential facilities.

Critical Facilities

Structures such as thermal and nuclear power plants, liquefied natural gas storage tanks, petrochemical facilities, offshore platforms, and dams are representative of structures considered to be critical facilities. During the past decade important advances have been made in the seismic design of nuclear power plants. Such designs now involve the investigation of design ground motions, the dynamic characteristics of foundation soils, soil-structure interaction, and the response of structures, equipment, and piping. It is significant that these methods of seismic design for nuclear power plants, which were developed in the United States, are now used in the design of power plants throughout the world. The earthquake problem of nuclear power plants has many special features that do not arise in the seismic design of other structures and facilities. The same statement can be made for many other critical facilities.

In 1981 the American Petroleum Institute (API) published its *Recommended Practice for Planning, Designing, and Constructing Fixed*



This reinforced concrete containment structure houses the nuclear reactor of the San Onofre power plant in California. This structure was designed on the basis of a dynamic analysis, using a 0.67-g design spectrum, to survive the maximum credible ground shaking.

Offshore Platforms. This report, which is based on the results of earthquake engineering research, discusses seismic design criteria, a seismic risk map for U.S. offshore platforms, the use of earthquake design spectra, normalized design procedures, and the development of a computer model for calculating stresses and strains.

The potential for consequences of a dam failure makes a high degree of safety in the design of such structures imperative. Dynamic analyses superimpose earthquake stresses on the stresses produced by water pressure and gravity loads on the dam, and the structure is then designed to withstand the effect of the combined stresses. Modern methods of seismic analysis and design, based on earthquake engineering research, are now employed by such agencies as the Bureau of Reclamation, the U.S. Army Corps of Engineers, and the California Department of Water Resources. The National Dam Inspection Act requires that both existing and new dams located in highly seismic regions be analyzed to determine their capability to resist earthquakes. Analyses of existing dams have revealed that certain dams in Wyoming, Tennessee, and California would not perform satisfactorily under a maximum seismic event. As a result, the water in their reservoirs has been lowered to a safe level, pending reconstruction. The full extent of the problem of hazardous old dams in seismic regions is not yet known.

Liquefied natural gas storage tanks pose special earthquake problems because of the temperature and combustibility of their contents. The seismic design of these facilities employs advanced methods of hazard assessment and dynamic analyses that would not have been possible without the results of earthquake engineering research.

Commercial, Financial, and Industrial Facilities

Earthquake research has had a very significant impact on commercial, financial, and industrial institutions. Organizations such as IBM, Standard Oil of California, Exxon, Hewlett-Packard, North American Aviation, the Dupont Corporation, and Bell Telephone Laboratories have applied the current state of knowledge in developing their own corporate earthquake preparedness plans. Many of these organizations have also developed their own building design and construction standards, which are sometimes more stringent than the applicable building codes. A strong motivation for these developments is the need to minimize any disruption of the industrial processes that are involved.

A decade ago financial institutions such as commercial banks, federal reserve banks, and insurance companies did not consider the impact of an earthquake on their ability to operate after an earthquake.

However, now that computers are handling most of the transactions, so that records could be lost, financial institutions have started planning for redundant functional systems, as well as for other preparedness measures to mitigate the impact of an earthquake. Insurance organizations such as Aetna Life and Travelers are evaluating their real estate investment portfolios and insurance exposures to determine the regional impact of earthquakes. Such direct use of current research in banking and financial institutions will certainly decrease the impact of an earthquake on society in general, and on commercial, industrial, and financial institutions in particular.

Government Facilities and Operations

Government operations are essential in times of crises, and minimizing the downtime before resumption of operations is an important consideration in the design of government facilities. Using state-of-the-art methods of analysis and design that have been developed since the San Fernando earthquake of 1971, various government agencies have initiated programs to evaluate the earthquake resistance of their major facilities. Navy bases (including drydocks), dams, and army facilities have been investigated, and strengthening methods have been developed to correct structural deficiencies. A triservice manual has been issued for the seismic design of new installations, and an interagency committee on seismic safety in construction has published guidelines for seismic safety in federal buildings.

Earthquake Planning, Preparedness, and Response

With the new knowledge gained in earthquake engineering during recent years, communities are learning to cope with their earthquake hazards. The value of seismic planning can be seen by comparing the results of the 1971 San Fernando, California, earthquake and the 1972 Managua, Nicaragua, earthquake, which had magnitudes of 6.4 and 6.2, respectively. In both instances the population of the strongly shaken area was approximately one million. The major difference was that the San Fernando earthquake affected a relatively new region of metropolitan Los Angeles in which construction was governed by earthquake requirements in the building code, whereas Managua had few buildings designed under requirements in a modern seismic code. In the San Fernando earthquake 65 people died, damage amounted to about $500 million (1971 dollars), and there was no long-term adverse social or economic disruption. In Managua more than 5,000 people died and the economic loss was estimated to be approximately equal to the gross national product. Nicaragua's economic base was completely disrupted, with strong social and political implications, and the reconstruction of the city and rebuilding of the economy is still not complete 10 years after the earthquake.

Such vast differences in the impact of the earthquakes were due in part to the suburban setting of San Fernando as contrasted with the metropolitan setting of Managua. But a greater factor was the earthquake-resistant design codes, the building construction technology, the disaster preparedness, the recovery capabilities, and the overall educational and technical know-how in the United States. These have continued to improve during the last decade. Table 4 gives elements of the policies to reduce losses that are now being implemented; these constitute the earthquake preparedness program. An analysis of the impacts that recent earthquakes have had in the United States leads to the conclusion that some of the policies listed in Table 4 have reduced economic losses, injuries, and deaths and hastened postearthquake recovery.

Some examples of the direct preearthquake actions that have been taken and have resulted in better overall preparedness are given below.

1. Building codes have been updated as better knowledge is developed. The recent ATC publication *Tentative Provisions for the Development of Seismic Regulations for Buildings*, which represents the

TABLE 4 Elements of Loss Reduction Policies

	Which Policy		
When	Direct	Indirect	Affected Parameter
Preearthquake	Building code development, land use planning, and zoning Warning systems Soil stabilization Land modification Strengthening of existing high-risk structures and facilities	Earthquake insurance Quality control of construction Licensing of design professionals Education of the public Prediction/warning procedures Emergency plans	Exposure Risk Primary and secondary hazards Vulnerability
Postearthquake	Source of funds for repair Bearing of loss Provision of disaster relief and reduced impact of earthquake	Education of the public Social and psychological help	Exposure Risk Hazard Vulnerability

state of the art in the formulation of model building codes, is a good example of how recent research results can be transferred into practical recommendations.

2. Recent developments in earthquake hazard assessment provide a better description of the hazard than was available in the past. Also, advanced methodologies in seismic hazard and risk analysis have given engineers, designers, and decision makers better tools in land use planning and in siting and designing critical facilities.

3. Pioneering efforts conducted or supported by the U.S. Geological Survey and individual states have produced hazard maps that can be used to categorize various seismic risks. Maps of the potential for strong ground motion, surface faulting, landslides, and soil liquefaction have been developed using methodologies and procedures that have come primarily from the research of the past 15 years. Such maps are now used for land use planning, for zoning, and for siting essential facilities in states such as California, Utah, Nevada, and Missouri.

4. As an example of actions taken by states, the Alquist-Priolo Special Studies Zones Act passed in California requires that a registered engineering geologist make a special geological study before a facility can be sited within 50 ft of an active fault. This is the minimum criterion for all structures. For special or critical structures, more restrictive criteria may be imposed.

5. The rehabilitation and strengthening of old buildings constitute one of the major problems facing governmental decision makers in seismically active regions. In future earthquakes the major causes of injury and loss of life will almost certainly be the collapse of old structures that were designed and built before modern building codes were developed. During recent years educational efforts have developed a widespread awareness of this problem. Many communities are now attempting to address this issue and to pass legislation to mitigate this risk. In 1981 the City of Los Angeles adopted an Earthquake Hazard Reduction in Existing Buildings ordinance, which shows how current awareness can be implemented in practice.

6. Many urban centers in recent years have prepared seismic safety elements as part of their general plans. These identify areas where major damage can be expected during an earthquake. Proximity to faults, geotechnical considerations, and the age of buildings help to determine the expected damage. Seismic safety elements also help in the planning and implementation of postearthquake recovery measures. The importance of such planning and implementation was demonstrated by two recent Italian earthquakes. The 1976 Friuli earthquake (magnitude 6.5) caused extensive damage and about 1,000 deaths in a region that had a well-defined economic base of small-scale light industries. After the earthquake the Italian government placed high priority on

reestablishing this economic base. There was no exodus of the labor force, and in just two years the economic and social base was thoroughly reestablished. In contrast, the Campania-Basilicata earthquake of 1980 (magnitude 7.2), which killed 3,100 people, struck an area that had no industrial base. It is clear that much more than two years will be required to overcome the economic and social disruption of this earthquake.

Approximately 30 million people live in the highly seismic regions of the United States, and perhaps another 100 million live in regions that are less seismic but where the possibility of destructive earthquakes cannot be ignored. The optimum course of action for the various states, counties, and cities involved have not been established, and even if these were known it would be very difficult to implement actions that affect 130 million people. Although significant progress has been made in earthquake planning, preparedness, and response, this difficult problem has not yet been completely solved.

Conclusions

During the past decade the application of research results to practical problems has advanced significantly. In some cases research has developed and improved existing methods, as in the seismic design of buildings; in other cases research is being applied in areas where practically nothing was done before 1970, as in the seismic design of equipment, LNG facilities, and offshore platforms. The field of earthquake engineering and seismic hazards has clearly expanded very much over what it was in 1970. The result is that as the results of research are applied to recognized problems, new problems arise that before now were not considered.

While research continues to seek solutions to problems not previously addressed, new knowledge in earthquake hazard mitigation is being synthesized for application. Various documents that represent such syntheses include:

- *Tentative Provisions for the Development of Seismic Regulations for Buildings* (ATC 1975)
- *Seismic Design Guidelines for Highway Bridges* (ATC/FHWA 1978)
- *The Current State of Knowledge of Lifeline Earthquake Engineering* (ASCE 1980 and 1981)
- *Methodology for Seismic Design of Single Family Dwellings* (ATC/HUD 1976)
- *Earthquake Spectra and Design* (EERI 1982)
- *Earthquake Design Criteria* (EERI 1982)

In reviewing the field, it has become clear that a very important element in applying the results of research is a continuing effort in education in a broad sense. Not only should research workers and practicing engineers be educated, but those in government agencies, industries, and other organizations need to know about earthquakes and earthquake countermeasures. The program of earthquake hazard mitigation has produced much new knowledge that is being applied to practical problems. The lag time between research and its application is shrinking as technical communities engaged in research and practice interact and as decision makers are educated in techniques of earthquake hazard mitigation. Governmental agencies and practitioners in the private sector are aware that earthquake hazard mitigation must use the new knowledge that research develops. Although the accomplishments cited in this chapter are impressive, the need for continued research is imperative to address the issues that remain unresolved in the reduction of earthquake hazard.

It will be important in the future for society to recognize the pervasiveness of earthquake hazard. Not only structures whose design is governed by building codes are threatened by ground shaking but so are all the activities of industry, commerce, public utilities, governments, and other organizations. Planning, designing, and constructing in seismic regions should always take into account the possibility of ground shaking and in this way avoid the construction of structures and facilities susceptible to damage. This will require identifying the seismic problems that can be encountered, solving the problems of research, and a broad educational effort. In seismic regions earthquakes should be considered part of the environment, just as rain, wind, and snow are parts of the environment.

3

Assessment of Earthquake Hazard

Preparing for future earthquakes requires knowledge of the seismic activity that can be expected. For example, an engineer about to design a structure would like to know precisely the ground shaking that the structure will experience during its lifetime, so that he can make an appropriate seismic design. Since earthquakes and earthquake ground shaking cannot be precisely predicted, all relevant information about earthquake hazard in the vicinity must be used.

The engineer can obtain this information with different degrees of thoroughness, depending on the importance of the project being designed and the quality of the scientific data base available. For example, ordinary buildings in the United States are governed by the earthquake design requirements of local building codes, and these normally include a seismic map that zones the country into five categories of expected intensity of shaking. For major projects such as dams, power plants, pipelines, and offshore drilling platforms, special studies are usually made to assess the earthquake hazard at the particular site, and the design criteria for the projects are then based on these studies. If the hazard assessment greatly overestimates the expected intensity of ground shaking, the cost of the project may be excessive; if, on the other hand, the expected intensity of ground shaking is seriously underestimated, the result may be costly damage and loss of life. Earthquake hazard assessment is therefore of great importance in coping with the practical aspects of the earthquake problem.

The assessment of earthquake hazard involves specifying the likelihood, magnitude, location, and nature of earthquakes that might have damaging effects in the region or at the site under consideration and estimating the intensity, duration, and frequency characteristics of the ground shaking. Everything that can be said in this context must originate in one or more of the following sources of data: (1) the history of felt earthquakes in the region, (2) the seismographic record of earthquake occurrence in the vicinity, (3) the recent geological history of the region, especially that within the past few hundred thousand years, and (4) accelerograms of strong ground shaking recorded during past earthquakes. The past five years have produced important scientific and engineering advances from improved data bases. Especially significant advances have been made in using geological evidence to evaluate earthquake hazard quantitatively. This chapter will emphasize these achievements, as well as the promise for future development. Local soil conditions can also have an important impact on the evaluation of seismic hazard, but this problem is considered in Chapter 5.

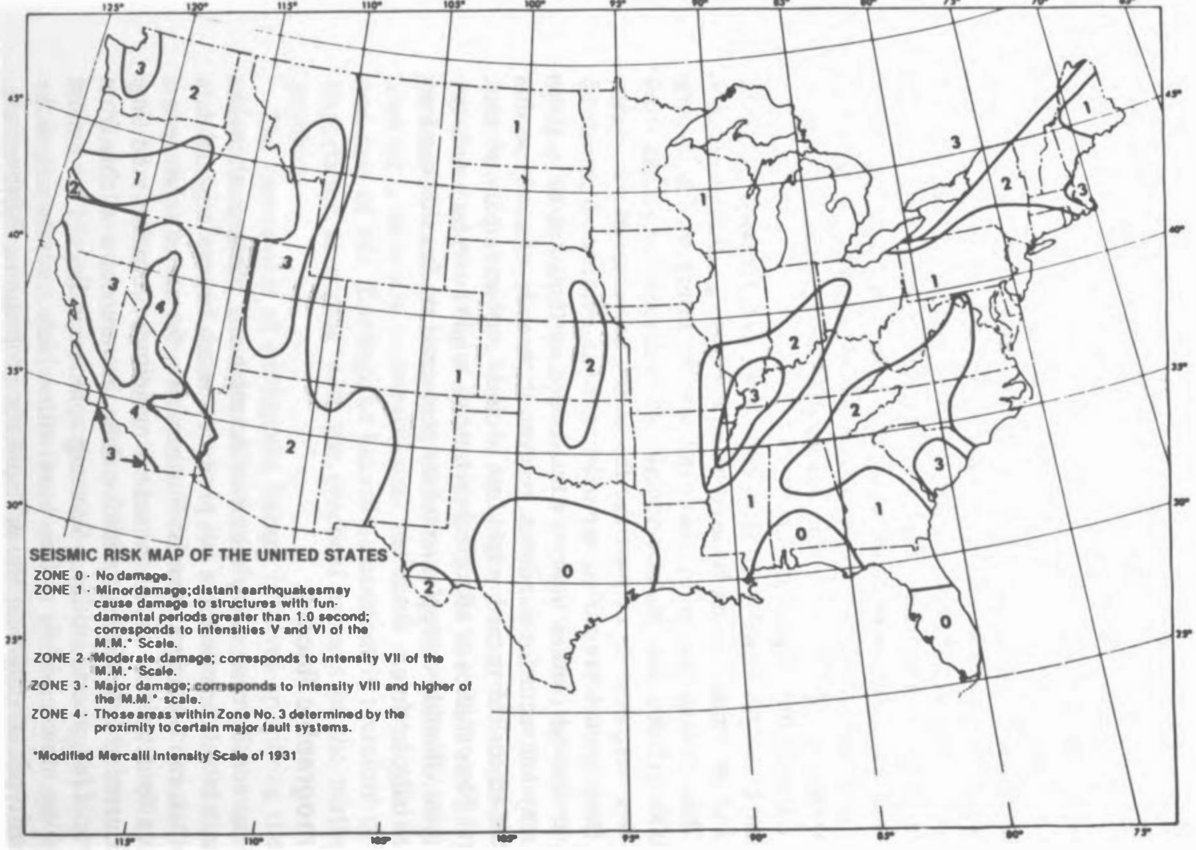
Historical Seismicity

However brief or inadequate the historical record of earthquakes may be for a given region, documenting this record is an essential first step in hazard assessment. The historical record of earthquakes that are known to have affected an area in the past is the most direct clue to the kinds of earthquakes that might affect that region in the future. Local published catalogs are not always adequate, and experience has shown that specific historical studies using local sources of data often yield considerable improvement.

Even if the historical record is complete over a period of years, considerable caution must be used when estimating future seismicity, for a short history may not reliably indicate the future. In China, with its 2,000- to 3,000-year historical record of earthquakes, the data show that over long periods of time the frequency of occurrence of large-magnitude events has varied appreciably. Also, evidence from worldwide geological studies indicates that major earthquakes on a given fault may not recur for hundreds, or even thousands, of years, so that a short historical record might not include any examples of such events. Thus studies of historical seismicity, while necessary and very important, should be supplemented by geological studies that can look farther back in time.

Seismographic Record

Because sensitive seismographs can detect many more earthquakes than can be felt, instruments can produce a much larger statistical data base than can historical records. Furthermore, the use of seismograph records to determine an earthquake's magnitude, location, and time of occurrence provides quantitative data that are not available from reports of felt ground motions. Seismographic recordings in the United States are now creating a data base with which analysts can make various types of statistical and probabilistic projections. Furthermore, the precise locations of earthquakes give important clues to the locations of active faults, areas of high and low activity, and other spatial parameters.

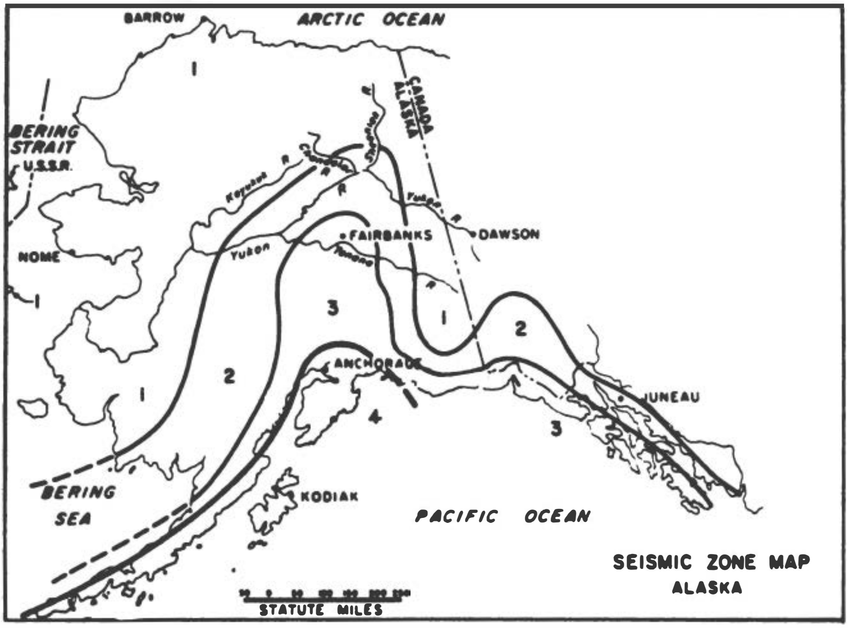


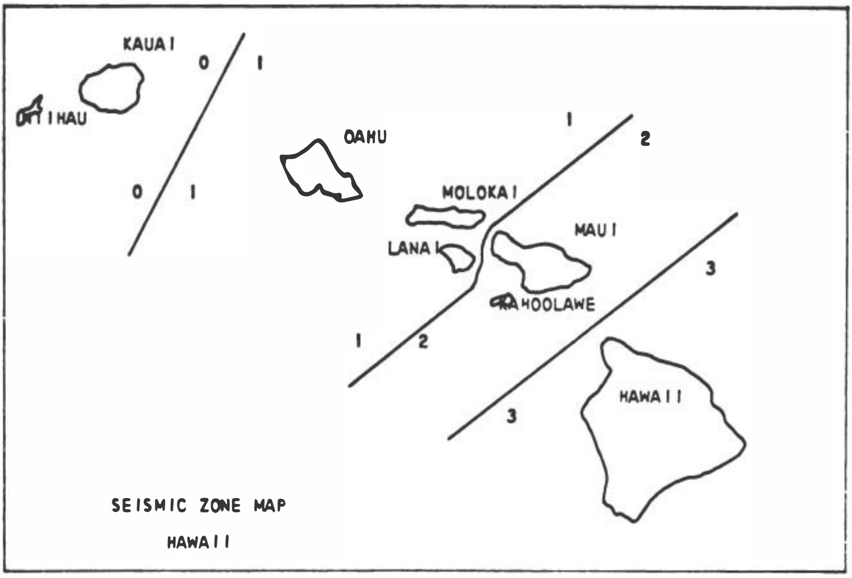
SEISMIC RISK MAP OF THE UNITED STATES

ZONE 0 - No damage.
ZONE 1 - Minordamage;distant earthquakesmay cause damage to structures with fundamental periods greater than 1.0 second; corresponds to intensities V and VI of the M.M.* Scale.
ZONE 2 - Moderate damage; corresponds to intensity VII of the M.M.* Scale.
ZONE 3 - Major damage; corresponds to intensity VIII and higher of the M.M.* scale.
ZONE 4 - Those areas within Zone No. 3 determined by the proximity to certain major fault systems.

*Modified Mercalli Intensity Scale of 1931

These zoning maps from the Uniform Building Code show the approximate seismic risk in different parts of the United States. Earthquake design requirements are based on these maps. However, the requirements are not effective unless city governments officially adopt and enforce them. Reproduced from the *Uniform Building Code, 1979 Edition*, copyright 1979, with permission from the publisher, the International Conference of Building Officials, Whittier, California.





Zoning maps—(*Continued*)

It must be recognized that a complete seismographic record for a given time period may not statistically represent the longer time period for which projections are desired (e.g., the 100-year service life of a dam). This is, of course, the same problem encountered in the historical record, but it is not always recognized when analyzing the copious data that seismographic catalogs may provide. The problem is particularly difficult for areas of low seismicity, such as parts of the eastern United States, where destructive earthquakes occur very infrequently. It is not clear how well a 50-year seismographic record represents long-term seismicity in these regions.

Better methods to analyze the occurrence of earthquakes statistically should be developed, methods that present the relevant information in a form most pertinent to hazard assessment. Such statistical developments must be based on a better knowledge of earthquake processes. In particular, they should consider improved data on the occurrence of earthquakes of magnitude 5.5 or greater, how the occurrence of large-magnitude earthquakes is related to the occurrence of small-magnitude events, how the frequency of occurrence varies over periods comparable to the lifetimes of structures, and so on.

One useful predictive technique has arisen in recent years from

The Dixie Valley, Nevada, earthquake of 1954 caused this large fault displacement. The shaking of this magnitude 7 earthquake was felt over an area of 200,000 square miles. Fortunately it was not near a city.

studies of highly seismic regions. Within a continuous zone of high long-term seismicity, such as along the Aleutian Islands or the west coast of South America, well-delineated segments that have been seismically quiescent for a number of years often have a large earthquake that abruptly fills the gap. This is called the ''seismic gap'' theory, and large gap-filling earthquakes in Mexico, Japan, Alaska, Chile, and other highly seismic zones have demonstrated its veracity. Identifying a seismic gap is therefore of great practical importance. The U.S.-supported Worldwide Standardized Seismographic Network (WWSSN) has been critical in identifying and studying seismic gaps, including two currently identified gaps in southern Alaska. Even in California, the highly seismic San Andreas fault presently has two distinct segments that are almost totally quiescent, and these seismic gaps are generally recognized as the most likely places for truly great earthquakes in California in the foreseeable future.

Geological Studies

The geological record deciphered from the earth's crust (paleoseismicity) has an advantage over historical and seismographic records in that it extends far enough back in time to provide information on long-term earthquake processes. The challenge in applying the technique, however, is to identify in some realistic and practical way the geological evidence left by past earthquakes. That is, just what in the geological record can be used to identify the occurrence of earthquakes hundreds or thousands of years in the past. Great progress has been made in this area in the past decade.

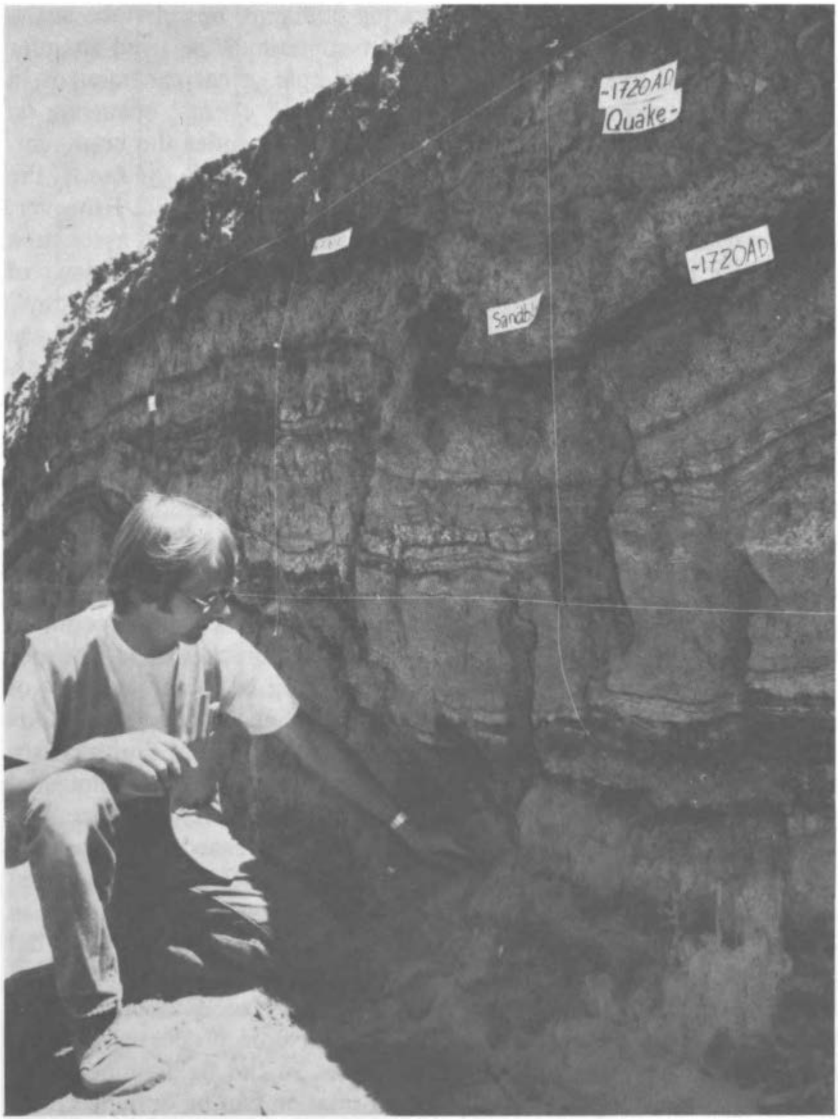
A major earthquake can leave a distinct geological record in several ways. First and foremost, the faulting that caused the earthquake may displace strata at shallow depths beneath the surface. It may also create a fault scarp on the surface that remains visible or is subsequently buried by younger strata and thus preserved for future examination. Secondly, the intense ground shaking in the central region of a large earthquake may produce effects on surficial soils, such as sandblows or landslides, that are preserved. Sandblows result from the liquefaction of water-saturated sand at depth, which then ''erupts'' through to the ground surface, leaving small volcanolike hillocks of sand.

Preserved geological features such as the above can best be observed in trenches that are excavated across fault zones. Recently, improvements in trenching and dating techniques have produced very significant results. Foremost among these is a series of trenches excavated across the San Andreas fault at Pallett Creek, northeast of Los Angeles. These trenches exposed several branches of the San Andreas fault, all within a few meters of one another, cutting a series of alternating sand and peat layers deposited during the past 2,000 years. The peat layers could be dated by radiometric methods. Fault offsets have also been dated in the older underlying strata, offsets that do not appear in the younger strata. All of these offsets indicate recurrent fault displacements in successive earthquakes during the interval in which the sediments were being deposited. Distinct evidence of sandblows also appears at a number of horizons, indicating heavy shaking at those times.

Putting together all the available evidence, research workers have been able to show that, in addition to the great historic earthquake of 1857, similar large prehistoric events have occurred along this segment of the San Andreas fault. They have established the following dates for these events: A.D. 260, 350, 590, 735, 845, 935, 1015, 1080, 1350, 1550, and 1720. Thus great earthquakes recur on the segment of the San Andreas fault opposite Los Angeles about every 150 years on the average, although such events have occurred as close together as 65 years and as far apart as 270 years. Since 125 years have passed since the last large earthquake on this segment of the fault, southern California clearly is in a dangerous period now. This has spurred state and local governments in California to undertake earthquake preparedness programs.

Similar field investigations have been made of the prominent Wasatch fault in Utah. These have identified fault displacements that indicate that damaging earthquakes have occurred along this fault approximately every 500 years on the average. The earthquake hazard in Utah is thus greater than the short historical record would indicate. The State of Utah now recognizes the existence of the hazard and has initiated a preparedness program.

Thus, for the first time, quantitative measures of the frequency of large earthquakes along a given fault segment are available. This information has important engineering implications for the formulation of building codes, for land use planning, and for the siting of critical facilities. Similar studies are now under way on other seismogenic faults throughout the world. One surprising result to date has been the great differences in degrees of earthquake activity among faults that would otherwise simply be classified as "active." The San Andreas fault, with its short recurrence interval, is highly active by worldwide standards. Other major faults—some of which have caused great historical earthquakes—are considerably less active, with recurrence intervals measured in thousands of years. The great variations in fault activity tend to make obsolete the arbitrary classification of faults as "active" or "inactive," for the degree of activity has great practical importance.

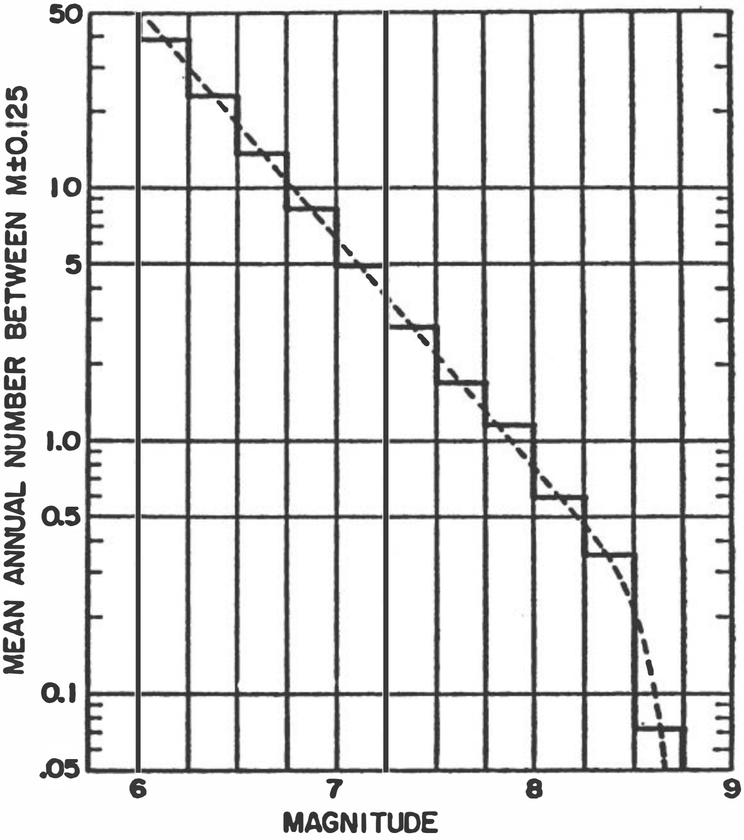


Trenching across the San Andreas fault permits radiometric dating of horizon levels and reveals evidence of fault displacements, sand blows, and other signs of past earthquakes. The A.D. 1720 layer is labeled, and relative vertical displacement can be seen below the label but not above. On this fault the major component of displacement is horizontal, perhaps 15 times greater than the vertical component. These studies have shown that over the past 1,500 years large earthquakes have occurred with an average recurrence interval of about 150 years. Since the last great earthquake on this segment of the fault (near Los Angeles) was the magnitude 8.3 Fort Tejon earthquake of 1857, this information on recurrence intervals is of great practical significance.

In areas where earthquake-generating faults are not obvious at the earth's surface, other phenomena can sometimes be used to infer earthquake recurrence intervals. For example, great earthquakes in Alaska have typically been "subduction zone" events, occurring on shallow dipping faults that lie many kilometers under the continent. Thus, although geophysical measurements can identify the faults, the faults cannot be studied with normal techniques in the field. However, great earthquakes on these faults have almost always been associated with major regional uplifts, such as the abrupt 10-m uplift of parts of Prince William Sound that accompanied the 1964 "Good Friday" Alaska earthquake (the largest U.S. earthquake of this century). These uplifts have left successive raised beaches along the shores of islands. On Middleton Island in the Gulf of Alaska, for example, five distinct raised beachlines have been dated with carbon-14 methods, and the resulting ages indicate that earthquakes comparable with that of 1964 have occurred on the average about every 850 years for the past 5,000 years.

Studies of the above-mentioned types obviously rely very heavily on absolute age dating of young geological materials, usually by radiometric techniques. Advances in these studies thus depend, in part, on the development of more accurate, quicker, and cheaper methods of age dating. A better understanding of the chronology of soil development will also advance these studies, since surficial soils are often the youngest materials broken by individual faults. Also, major earthquakes that have occurred during the past few thousand years have often left fault scarps preserved on the ground surface, and these are potential sources of information. An increased understanding of how scarps degrade over the years would help considerably in quantitative hazard assessment. Significant progress has been made in each of these fields within the past five years, and it is essential that such progress continue.

The occurrence of a large earthquake with surface faulting provides an unparalleled opportunity for studying tectonic processes, so it is important to be prepared to make studies in the field immediately following the earthquake. Valuable information can be obtained from foreign earthquakes as well as from U.S. earthquakes, particularly since foreign earthquakes occur much more frequently. For example, postearthquake field studies of the 1980 El Asnam, Algeria, earthquake have provided a better understanding of the tectonic processes associated with thrust faults, such as those present in much of the American West, and the field studies of the great earthquake in southern Chile (magnitude 8.5) considerably enhanced the understanding of the regional framework for the remarkably similar great Alaska earthquake (magnitude 8.4). To improve our understanding of earthquake hazards, it is essential that postearthquake field investigations continue to be



This bar graph shows the number of large earthquakes expected in the world per year. For example, five earthquakes of magnitude 7 to magnitude 7.25 can be expected per year. The graph is based on a 40-year statistical sample. The dotted line, representing the mean annual number of earthquakes in each quarter unit of magnitude, bends off at about magnitude 8.6, indicating that larger earthquakes are not observed to occur. Earthquakes of magnitude 6 or greater have the potential for severe damage and therefore are of prime importance for earthquake engineering research. Reliable bar graphs cannot be drawn for some local regions if the statistical sample is too small. (The magnitude plotted in the graph is M_L (local) for the smaller values and M_S (surface) for the larger values.)

encouraged and supported, that they include significant foreign earthquakes, that they be organized in a timely fashion before critical evidence has disappeared, and that they cover a wide spectrum of expertise.

Eastern Versus Western Earthquakes

One of the principal difficulties in evaluating earthquake hazard in the United States has revolved around the differences between the eastern and western parts of the country, with the dividing line the eastern front of the Rocky Mountains. Whereas most large western earthquakes have been clearly related to faults of considerable length that can be identified and studied at the ground surface, most eastern earthquakes can not be directly related to identifiable faults. There can be little doubt that eastern earthquakes, such as those near Charleston, South Carolina, in 1886 and near Boston in 1755, originated in fault displacements at depth, but these faults are yet to be identified, especially near the ground surface. Thus new techniques must be developed to study such events. In recent years a "tectonic province" approach has been developed to evaluate seismic hazard for critical facilities in the East. It assumes that the maximum earthquake that has historically occurred within a tectonic province can equally well happen anywhere else in the province. But this technique is far from satisfactory. A recent National Academy of Sciences study on the siting of critical facilities concluded that "although at present the tectonic province approach may be the only practical method for siting critical facilities in parts of the eastern United States, in the long run, we must work toward a procedure for the East that is similar to that in the West—one that is based on identifying individual geological structures responsible for earthquakes."*

The past few years have brought considerable progress in identifying such causative structures in the region of the 1811-1812 New Madrid, Missouri, earthquakes. But the needed understanding of why earthquakes occur in the East and why they occur where they do has yet to be achieved, and research is urgently needed to answer these questions.

Maximum Earthquake Size

An often-asked practical question, particularly for critical structures such as dams and nuclear power plants, is, "What is the maximum earthquake that can occur in a given region." The question is almost impossible to answer unless it includes a time frame. That is, the maximum earthquake that might occur within a typical 100-year period will usually be much smaller than one that might occur in the same area during a 100,000-year period. While it is true that a "maximum credible" earthquake may exist that geologically cannot be exceeded no matter how long one waits, this is an exceedingly difficult concept

---

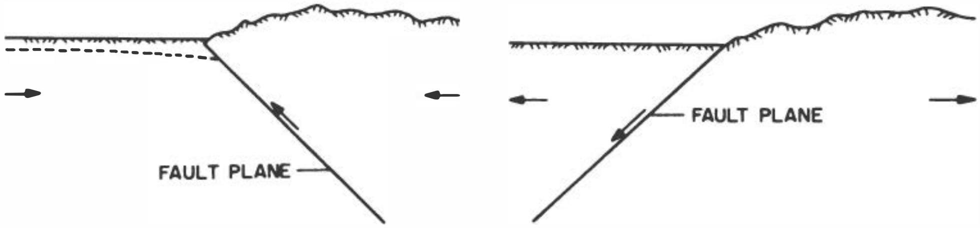
* Panel on Earthquake Problems Related to the Siting of Critical Facilities, Committee on Seismology, *Earthquake Research for the Safer Siting of Critical Facilities,* National Academy of Sciences, Washington, D.C., 1980.

to quantify, and what is credible to one person may not be to another. Thus an increasing trend has developed toward probabilistic stipulations of maximum earthquakes. The geologist or seismologist, or even the engineer, should not have to decide alone whether a critical project, for example, should be designed for a 100-year or a 100,000-year maximum earthquake. This decision, which involves considering the acceptable level of risk, should receive input from the owner and the public, who usually must either accept the risk or pay the cost of mitigating it. Proposed projects not uncommonly now consider several maximum earthquakes corresponding to several degrees of likelihood. The project planners must then decide which of these represents the appropriate level of safety, recognizing that "absolute" safety is an unrealistic goal.

Factors that are usually considered in the stipulation of maximum earthquakes include (1) the instrumental and historical record of large earthquakes in the general area, (2) comparisons with geologically similar areas elsewhere in the world that may have a more complete historical or instrumental record, and (3) the nature of local faults whose displacement might cause the maximum event. In particular, seismologists have long recognized that large earthquakes do not occur on short faults, and recent correlations based on numerous worldwide observations of the length of fault rupture versus earthquake magnitude give considerable insight into the maximum events that a given fault can credibly produce. Further differences are observed for thrust faults, normal faults, and strike-slip faults. Consequently, the deformational processes and tectonic style in the region must be understood to estimate the maximum earthquake. Additional clues may come from trenches excavated across faults, where it is sometimes possible to observe displacements associated with specific prehistoric earthquakes, and thus to infer something about their probable magnitudes. The uncertainties associated with the foregoing items are, of course, reflected in seismic zoning maps; such maps should properly specify levels of uncertainty as well as relative hazard.

Probabilistic Approaches

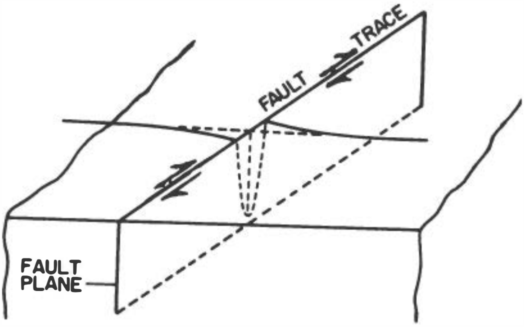
The preceding sections have mentioned the problems and challenges involved in developing more satisfactory statistical and probabilistic approaches to assessing earthquake hazard. Despite the many problems, such approaches will clearly increase in importance as time goes by, in the effort to systematize and quantify hazard assessment. It is important to encourage research in this area since off-the-shelf methods are often inadequate.



A. Thrust faulting under horizontal compressive strains. Example: San Fernando, California; February 9, 1971; magnitude 6.5.

B. Normal faulting resulting from extensional strains. Example: Dixie Valley, Nevada; December 16, 1954; magnitude 7.1.

C. Underthrust faulting in a subduction zone. Example: Alaska; March 27, 1964; magnitude 8.4.



D. Strike-slip displacement on a vertical fault plane. Example: San Francisco; April 18, 1906; magnitude 8.2.

These four types of faulting generate destructive earthquakes in the United States. Ground shaking close to the causative fault can be significantly affected by the type of faulting. For earthquakes smaller than the above, the fault displacements usually do not reach the surface of the ground, and the entire faulting process may occur at considerable depth.

The fragmentary nature of the statistical record of earthquakes constrains the analyses that can be done. To overcome these constraints, assumptions about physical or statistical processes are customarily made. The results of the statistical analyses thus contain information both about the seismic record and about the implicit assumptions, so that the reliability of an analysis strongly depends on the quality of the assumptions. To improve the statistical analyses requires a better understanding of where, when, and why earthquakes occur, to guide the statistical assumptions. Research should also seek the optimum statistical methods of analyzing fragmentary data. These methods themselves may depend on the results of even more basic research directed toward determining whether or not an earthquake occurrence can be described as a stationary or nonstationary process.

Earthquake Prediction

Earthquake prediction has the potential to make important contributions to earthquake engineering and disaster planning. As yet, however, it remains a complex and exciting scientific goal, for nowhere in the world is routine earthquake prediction a reality. It would be a mistake for engineers to assume that the near future will bring routine short-term predictions (e.g., to predict the size and location of events that will occur within weeks or months). Furthermore, even if eventually successful, the capability to make short-term predictions will certainly have a greater impact on disaster planning and earthquake preparation than on normal engineering efforts. In the design of a structure, or in land use planning, the engineer must necessarily consider the likelihood of events that might occur over the total life of the project—for example, 50 years for a building, or 100 years for a dam. Thus short-term predictions are somewhat irrelevant to most engineering planning, regardless of how valuable they may be in disaster preparation. (An exception would be the planning of practical engineering techniques to *respond* to a short-term prediction, for example by shutting down a critical facility.) Long-term predictions (such as in the southern

Satellite photograph of the Los Angeles region clearly shows the San Andreas fault running across the picture. Aerial photography has been developed as a powerful tool in identifying potentially hazardous faults.

California area) are more feasible technically and more useful to engineering planning.

Nevertheless, scientific research aimed at short-term predictions is not entirely distinct from that aimed at long-term predictions and probabilistic statements, so the engineering community has considerable stake in the overall program of prediction research. For example, during the last five years many of the dense seismological networks in California have been supported largely by funds for earthquake prediction, and yet the output of these networks forms one of the principal bases for probabilistic approaches to evaluating earthquake hazard.

Reservoir-Induced Earthquakes

A particularly worrisome engineering problem concerns earthquakes that have been triggered by the filling of reservoirs. At least two major dams (Koyna Dam in India and Hsinfengkiang Dam in China) have been seriously damaged by reservoir-induced earthquakes, both of which exceeded magnitude 6. Some 70 other dams and reservoirs have experienced induced activity at either macro- or micro-earthquake levels. Although this represents only a small proportion of the total number of dams worldwide, engineers cannot afford to dismiss the possibility of triggered earthquakes associated with large and deep reservoirs at any major dam now being planned.

Research on the subject during the past decade has identified several factors that appear to have had an influence on reservoir-triggered earthquakes. However, no completely diagnostic geological, hydrological, or geophysical criteria have been identified that can indicate exactly where reservoir-induced earthquakes are possible or impossible. For example, such events have occurred in a wide variety of geological settings, including areas of normally low seismicity and areas not previously known to have active faults. Statistical summaries do indicate that induced earthquakes are more likely to occur near large and deep reservoirs, and recent borehole studies of the hydrological and stress regimes near reservoirs have been very promising in the effort to understand the mechanics of the triggering process. But routine identification of dangerous areas—particularly for the larger and deeper shocks—remains elusive. Nevertheless, this appears to be a field where the implementation of a vigorous research effort could produce significant progress in the next decade. In the meantime, engineers have little choice but to assume that, virtually regardless of the geological environment, high dams retaining large reservoirs must be designed while recognizing the possibility of a large induced earthquake centered nearby.

Strong Earthquake Ground Motions

The ultimate objective of earthquake hazard assessment is to specify the ground shaking that will govern the seismic design of a structure or facility. To assign an earthquake ground motion for a structure, a stipulation must be made of the magnitude and location of the most severe event to be considered and then an inference is made of a probable ground motion at the site based on actual accelerograph records obtained elsewhere from earthquakes of similar magnitudes at similar distances. The reliability of this method clearly depends on having an adequate data base of recorded ground motions. Consequently, it is desirable that several accelerograms be available that have been recorded during earthquakes of the same magnitude and at the same distance from the site, at locations having similar local geological conditions and soil conditions, and for source mechanisms having different styles of faulting, depths of focus, and other rupture parameters. The present data base is not large enough for purposes of hazard assessment.

Conclusion

An improved ability to assess earthquake hazard can provide important benefits. If the hazard is underestimated, as was the case in Tangshan, China, a great disaster can result. If the hazard is overestimated, on the other hand, unwarranted expenditures can take place. There should be continuing research on improving hazard assessment in the United States, and this effort should interact closely with similar efforts in foreign countries.

4

Earthquake Ground Motion

The quantitative description of earthquake ground motion is the starting point for any scientific investigation of earthquake phenomena. As such, it is also the indispensable foundation for the development of earthquake engineering. Recordings of strong earthquake ground motions are used in the analysis and design of many important structures, and they provide the basic information on the characteristics of ground shaking that is used to set design criteria for nuclear power plants, high-rise buildings, major dams, offshore platforms, and other structures. Such recordings also form the basic data for research on the source mechanisms of destructive earthquakes.

Major advances have marked the study of earthquake ground motion during the past decade, but it is now evident that new planning and organizational strategies are needed to ensure continued optimal development. Much of the recent progress has resulted from the greatly expanded and improved instrumentation networks that collect basic data and from the much enlarged data bank they have provided. Many of the new problems relate to the rapidly escalating costs of expanding these networks and to uncertainties over when a principle of diminishing returns may take effect.

Four of the seven major recommendations made by the Panel on Ground Motion in the 1969 National Research Council-National Academy of Engineering publication *Earthquake Engineering Research* directly related to improvements in strong-motion accelerographs and to increasing their deployment throughout the seismic regions of the world. These recommendations have been a factor in the rapid increase of installed accelerographs, which have multiplied fivefold in number. Today many hundreds of excellent earthquake accelerograms are available for recent earthquakes. A summary of the accelerograms obtained during four recent important earthquakes reveals this rich increase in our basic data resources.

1. The San Fernando earthquake of February 9, 1971, occurred near the center of one of the most densely instrumented regions of the world. These instruments had been installed by building owners, power companies, nuclear reactor operators, government agencies, and other groups. Two hundred and forty-one three-component accelerograms

were obtained, most of them within 75 km of the epicenter. The records included one important measurement adjacent to Pacoima Dam, which was very close to the epicenter. This record included the highest acceleration peak value recorded up to that time. Simultaneous readings at three different elevations in some 40 high-rise buildings were also recorded, providing an unprecedented opportunity to compare measured responses with design calculations. Both seismologically and with regard to earthquake-resistant design, this set of records has been of major importance.

2. The Imperial Valley earthquake of October 15, 1979, occurred in a highly seismic region from which records of many different earthquakes had been obtained. Among the approximately 40 free-field sites in the epicentral region that produced excellent records was an important set of accelerograms from a 13-station linear array transverse to the causative fault, with all but one within 10 km of the fault. One of the stations, located in the V between the main fault and a branch fault, was 1 km from the main fault, and it recorded a vertical high-frequency peak acceleration of 1.74 g, the highest value directly measured so far. A recently designed multistory building 7 km from the fault, which suffered major structural damage, was instrumented with a central recorder and 13 accelerometer transducers. A highway bridge within 2 km of the fault, which was essentially undamaged, was instrumented with two central recorders and 26 transducers. These important records are being analyzed and will contribute substantially to the study of structural response to earthquakes.

3. The Friuli earthquake of May 6, 1976, was centered in a region of northern Italy well covered by an accelerograph network. Ten stations operating in the epicentral region before the main shock and an additional eight stations installed afterward to study aftershocks produced over 200 accelerograms. Records were obtained from a wide variety of distances and soil conditions, and analysis of them is revealing many important features of earthquake ground motion in the region.

4. The Montenegro earthquake of April 15, 1979, was recorded by 29 accelerographs and 21 seismoscopes of the Yugoslavian network. Over 200 accelerograms and more than 40 seismoscope records were obtained within one month. No records were lost because of instrument malfunctions, indicating that, with proper installation and maintenance, modern commercially available accelerographs have a high level of field reliability.

These basic ground motion measurements are of major importance to earthquake engineers because they make it possible to (1) compare various earthquakes in different parts of the world according to their overall characteristics and potential for structural damage, (2) interpret the behavior of particular structures and decide whether damage resulted mainly from strong ground motion or a weakness in the structure, (3) quantify the basic parameters of the processes of earthquake generation and transmission so that seismological investigations can be interpreted and applied to engineering problems, and (4) provide the extensive data bank necessary to deal with the large number of variables involved in the generation and propagation of earthquake waves and their interactions with structures.

A very considerable portion of the earthquake engineering research program of recent years has concentrated on the problem of recording destructive ground motions. Twenty-five years ago rather primitive accelerographs for recording strong ground shaking were installed at only 38 stations in all of the United States, and most earthquakes were too far from an instrument for the strong shaking to be recorded. As new and improved instruments were developed, and as knowledge of earthquakes and of the need to record ground motions was disseminated, a substantial number of instruments were installed. This is clearly a success of the earthquake engineering research program in the United States, and a number of foreign countries have emulated it using instruments purchased in the United States.

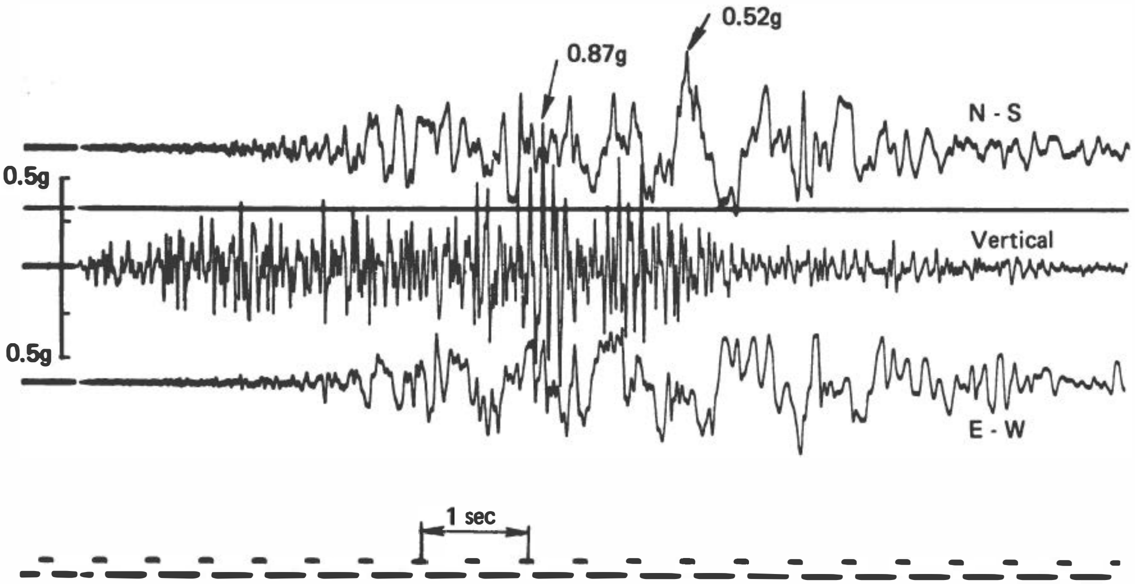
The existing strong-motion accelerographs in the United States have been installed by a large number of organizations for special purposes. As a result, the locations of the instruments are far from optimum for research purposes. A U.S. strong-motion program is needed to coordinate between the installers of instruments and the users of data. This was emphasized in the report of the U.S. National Workshop on Strong-Motion Earthquake Instrumentation, which was held in Santa Barbara, California, in April 1981.* The workshop recommended that a National Committee on Strong Earthquake Motions be established, under the aegis of the National Research Council, to plan a national program and to coordinate efforts. This should certainly be done.

The Measurement of Strong Ground Motion

The three-component, mechanical-optical, 70-mm-film recording accelerograph, which accounts for the vast majority of the some 5,000 instruments now deployed throughout the world, has resulted from several generations of design development and has achieved a high level of effectiveness. The analog film record has a number of advantages, including the widespread availability of processing facilities and the ready availability of data. A disadvantage for dense networks

---

* Iwan, W. D. (ed.), *U.S. Strong-Motion Earthquake Instrumentation,* California Institute of Technology, Pasadena, California, 1981.



This ground shaking was recorded by a strong-motion accelerograph during the 1981 Westmorland, California, earthquake. The recording instrument was close to the causative fault and the faulting was at a shallow depth, so the ground motions were relatively intense for a magnitude 5.6 earthquake. As is typical for recorded U.S. earthquakes, the vertical motion had higher frequencies than did the two horizontal components of shaking. The strong phase of shaking had a duration of about 4 seconds; for a magnitude 8 earthquake the strong phase would be about 30 seconds. The horizontal motions are composed mainly of shear waves, which travel with a speed of approximately 2 miles per second. The vertical motion is composed mainly of compression waves, which travel with a speed of approximately 3 miles per second, thus arriving 1 second earlier for about every 6 miles traveled from the common origin. The instrument is turned on by a trigger that senses vertical motion and is then turned off when the shaking stops.

that generate a large number of records is the relatively slow analog trace digitization that is often employed. This problem has been mitigated to some extent by the development of completely automatic scanning digitizers, which are now available at a number of data processing centers.

All strong-motion instrumentation systems now in use or being designed are digital systems in the sense that important stages of signal conditioning and data processing occur in a digital format. All such systems are also analog systems in the sense that the basic transducer is an analog device. The basic differences between systems lie in the point at which analog-digital conversions take place and in how these conversions are done.

The rapid development of digital data recording and processing has opened new possibilities for the design of strong-motion accelerographs. Among the potential advantages of direct digital recording are the following. (1) A memory can easily be incorporated to recover the first ground motions. (2) A wide dynamic range, extended if necessary by gain ranging, makes it possible to combine seismological and earthquake engineering investigations. (3) Data processing is simplified and speeded up to the extent that separate digitization processes after recording are not required. (4) Using microprocessor techniques, complicated starting algorithms can be incorporated and parameter change, including the use of various transducers, can be made very flexible.

In their present commercially available forms, digital accelerographs also have certain disadvantages, some of which natural design evolutions will no doubt overcome. (1) Their high power requirements significantly reduce stand-by time after an external loss of power. The stand-by time is typically several days rather than the several months common for analog accelerographs. (2) Their increased overall complexity requires more frequent field service and a higher level of training for field technicians. (3) Instrumentation costs are significantly higher. (4) More elaborate data processing systems may be necessary to prepare digital tapes from the field for computer processing.

Although the current types of systems for motion sensing, signal conditioning, and data processing are in general satisfactory for acquiring most of the ground motion data required by earthquake engineers, there are some points at which extensions of present capabilities would be desirable. Most important is an extended frequency range, which could provide both the information at higher frequencies needed to calculate certain machinery and equipment responses and the very long period data required to study such phenomena as the movement of water in reservoirs.

Strong-motion instrumentation is now passing through a period of rapid change. Currently available digital systems have successfully recorded strong earthquake ground motion under field conditions, but none of them has yet accumulated the years of field testing under unattended conditions needed to establish their long-term reliability, a factor that is of decisive importance to earthquake engineering.

Recommendation

The increasing cost and complexity of modern measurement technology, and the wide range of choices to be considered in designing instrumentation systems, makes more comprehensive studies of optimal configurations essential. Such investigations should include a consideration of:

a. The optimal division of function between field and laboratory.

b. The optimal match between the noise spectra of the instrumentation system and the spectra of measured quantities.

c. Full exploitation of modern techniques of direct digital recording and data processing, consistent with economic constraints and field reliability.

d. Increased development of systems with wide dynamic and frequency ranges for joint seismological and earthquake engineering applications.

Networks and Arrays

The first strong-motion accelerographs were independent stations at sites having a high probability of strong earthquake ground motion in the near future. As the number of accelerographs multiplied, the assemblage of instruments began to be seen as a network, whose primary function was to ensure that no earthquake would occur anywhere near the network without being recorded by at least one accelerograph. This modest goal has now been achieved for many important seismic regions in the world, but there remain many other highly seismic regions for which even this minimal objective has not yet been attained.

A network may be defined as any group of instruments having some common feature, such as management, maintenance, or data processing. Each station of the network can independently produce information of value, but the total information from the network is greater than the sum of the parts, since relationships between measurements at various sites can be established.

Very early in the development of strong ground motion instrumentation the idea emerged of deploying a number of interconnected instruments to study in detail particular features of ground motion or structural response. Such an interrelated group of instruments, which may or may not also be part of a broader network, is called an array. The first arrays were structural arrays installed in tall buildings. They usually involved three accelerographs, one at ground level to record input ground motions, and two at upper-story locations to define the modes of structural response. The three accelerographs were hard-wired so that common time signals would synchronize the records. Presently there are hundreds of high-rise buildings in the world instrumented in this way, and structural arrays involving multiple transducers recording at central points have been installed in many dams, bridges, power plants, and buildings.

The next development in array design sought to study ground motion itself. One of the first ground motion arrays was a line of accelerographs located transverse to the San Andreas fault near Parkfield, California. Because of this array, the Parkfield earthquake of 1966 produced valuable information about the attenuation of ground motion with distance from the fault and about details of ground motion in the immediate vicinity of the fault.

Ideas of network and array design were brought to a focus in 1978 by the International Workshop on Strong Motion Earthquake Instrument Arrays in Honolulu, Hawaii, which was sponsored by the National Science Foundation (NSF) and the United Nations Educational, Scientific and Cultural Organization (UNESCO). This workshop identified 28 sites in the world that combined high seismicity, accessibility, and the presence of features of geologic or engineering interest to make them favorable locations for instrument arrays. Six of the sites were selected as high-priority areas, and the workshop strongly recommended that instruments be installed there. The judgment of the workshop was confirmed by strong earthquakes at two of the high-priority sites within about a year of the conference.

The first major ground motion array to be installed in response to the Honolulu recommendations, and the first to exploit modern instrument technology fully, was the Taiwan array. This geometric array of 37 digital accelerographs in three concentric circles with an outer radius of 2 km was designed, installed, and is being operated by the Institute of Earth Sciences and National Taiwan University in cooperation with the University of California at Berkeley. The accelerographs have high-accuracy internal clocks for common timing and digital memories for first motion information. Since the array was installed in 1980, several strong earthquakes very near to it have provided much information for both seismologists and earthquake engineers.

From such arrays earthquake engineers can expect to learn much more about such important factors as the spatial variation of ground motion over short distances (on the order of the dimensions of engineering structures), the variation of ground motion with depth, and the correlations between motions in different directions at a point. These are matters of key importance in applying much current theoretical work in soil-structure interaction.

Under the stimulus of the Honolulu workshop, several other arrays are in various stages of design and implementation. An array has been designed and funded and the instruments have been procured for a 50-accelerograph network with highly accurate timing in the Himalayan regions of India. A special array has also been designed and funded for location near Beijing in the People's Republic of China. Preliminary planning has occurred and proposals have been made for special purpose arrays in Mexico, Turkey, and Greece.

Another product of the Honolulu workshop was the formation of the International Strong Motion Arrays Council, which is under the auspices of the International Association for Earthquake Engineering (IAEE) with UNESCO support. This committee hopes to play a coordinating role in the areas of development, data analysis, and data dissemination for the many instrument networks and arrays now forming.

The rapid expansion of networks and arrays throughout the world has created a series of new problems for earthquake engineering. The costs of instrument acquisition, maintenance, and data collection and analysis are mounting rapidly, and questions of optimal resource management are now of pressing importance. A proper division of resources between the various elements of earthquake engineering demands that priorities be studied much more carefully than they have been in the past.

Recommendation

The number of strong-motion accelerographs in the world has now grown to the point at which major problems of maintenance, data processing, and data dissemination are appearing. Additional increases in strong-motion instrumentation, which are essential for some seismic areas of the world, should proceed only after detailed studies of optimal combinations of single sites, networks, and special arrays. Careful thought should also be given to their integration with existing instrumentation systems. However, a number of highly seismic regions in the world, with populations exposed to a high seismic hazard, still have no adequate instrumentation for measuring destructive earthquake ground motion. The minimal goal of at least one measurement of damaging ground motion for every destructive earthquake, no matter where it occurs, should be sought.

Data Processing

From recordings of strong ground motion made in the field, earthquake engineers wish to derive the maximum possible information about ground displacements, velocities, and accelerations and about the associated frequency spectra over as wide a dynamic and frequency range as is feasible within the cost constraints of instrument deployment, maintenance, and data processing. None of these significant parameters of ground motion is directly measured by the current commercial instrumentation systems over the desired frequency range. Hence data corrections and extensions of various kinds are a necessity for all measurements. For a number of technical reasons, the instrumentation system that most nearly meets all practical requirements—simplicity, ruggedness, ease of installation and calibration, and long-range field reliability—produces outputs closely proportional to ground acceleration over the frequency range most often involved in earthquake engineering calculations. It is in this sense that the basic instruments used for strong ground motion and structural response are called "strong-motion accelerographs."

Methods for extending the frequency range of accelerographs by introducing transducer corrections, and for minimizing various sources of instrumental and digitization noise with digital filter techniques, thus permitting the accurate calculation of other ground motion quantities, have been worked out in considerable detail and are widely used in all countries. Investigations have shown that alternate data processing techniques produce essentially the same result, and there is general agreement as to the accuracy of present-day measurements when they are made with care and processed with the most modern procedures. Further improvements in data processing are likely to consist of gradual improvements in the computational aspects of the problem and greater ease in transmitting digital data from the field to the laboratory to the final user.

Data Dissemination

As the global data bank of strong-motion measurements grows at a rapid pace, the problem of data dissemination is causing increasing concern. The situation is further complicated by a tendency in many countries toward more and more agencies engaged in data acquisition and processing. This matter is being addressed by the IAEE's International Strong Motion Arrays Council, but so far no completely effective organizational procedures have emerged.

Small-scale demonstrations have shown the effectiveness of computerized data retrieval systems for strong-motion data, and this is clearly a field in which such modern data retrieval systems could be easily applied. The main requirement for successful initiatives in this area is a reasonably long-range funding commitment, until an educational program can make the project self-sustaining.

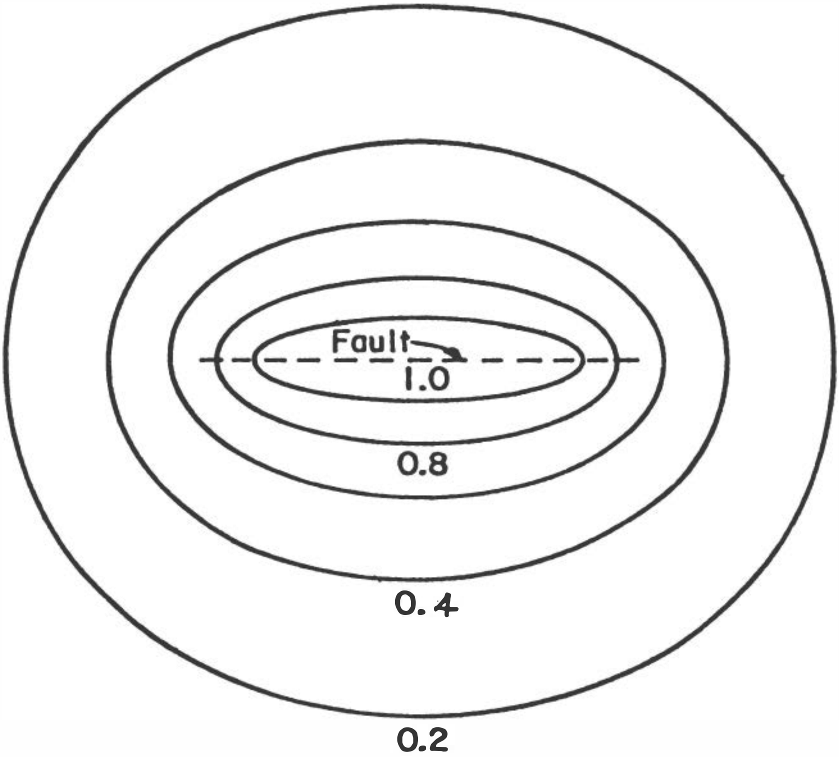
Recommendation

A major effort should be made to increase the availability of past ground motion measurements in a standard format to all investigators in all countries. Much existing information is not used to full advantage because investigators do not know about it or do not know how to get it in a suitable form. Modern computerized data retrieval systems should be able to solve this problem, given stable long-term organization and funding.

Data Interpretation

For several seismic regions in the world, the data bank of strong-motion measurements is sufficiently large that meaningful statistical investigations can begin. Most commonly, regression analyses are made for various quantities such as peak ground acceleration or spectrum ordinates. These regressions are based on three variables—earthquake magnitude, distance from the site to the point of major seismic energy release, and a simplified local soil parameter. Such analyses usually result in reasonably stable averages, and for some regions, such as Japan or the western United States, these average values are clearly well determined and not likely to change drastically with additional data. The problem is the very large dispersion—usually an order of magnitude or more—which will be very difficult to reduce significantly. The problem has been greatly oversimplified and many more variables will have to be introduced, though many of these complications have been widely recognized. Clearly, surface ground motion can be much influenced by such factors as (1) details of energy transformation in the focal region, (2) transmission path effects, involving nonuniform layers, surface topography, focusing effects, etc., and (3) local geology and soil conditions. But there is not now enough information on most of these factors to permit their inclusion in regression analyses. As seismological and earthquake engineering research proceeds, we can expect a gradual narrowing of the presently unacceptable dispersion limits.

A striking example of how difficult it is to obtain very basic information needed to interpret strong-motion accelerograms is the lack of accurate information on local soil and geological conditions at

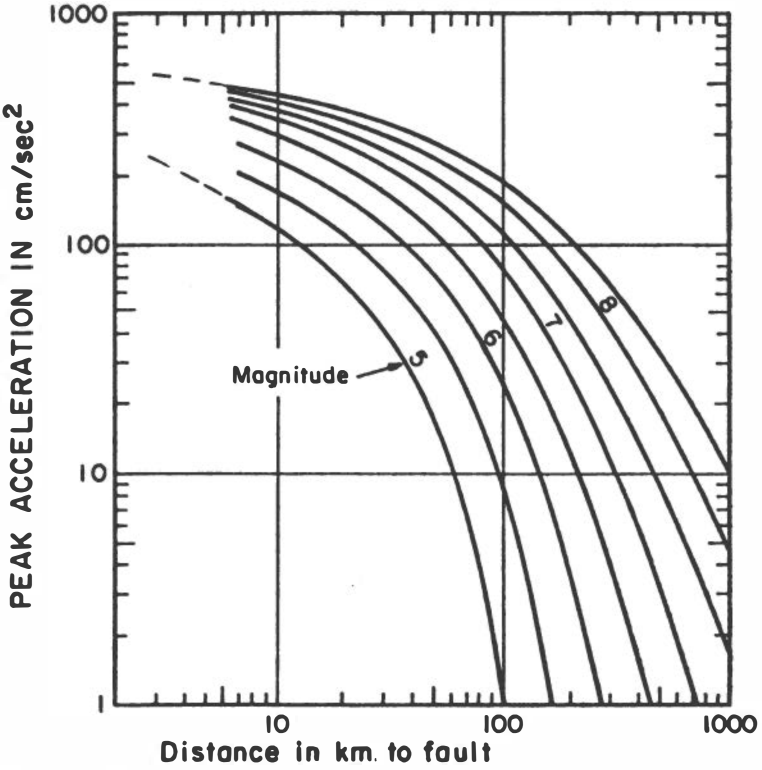


Idealized contour lines of shaking intensity show how the intensity of motion decreases with distance from the causative fault. For a real earthquake the contour lines are irregular, reflecting the details of the source mechanism, the geology of the travel path, and local geology. The attenuation is due to two causes: (1) geometric attenuation as the seismic energy spreads over larger volumes of material (this is particularly effective in the region of strong shaking) and (2) energy dispersion and dissipation due to inhomogeneities and other properties of the rock through which the waves pass (this nongeometric attenuation is particularly effective at larger distances from the fault). The above curves are based on scanty data, because few strong earthquake ground motions have been recorded. For instance, no recordings have ever been made near the strong shaking of an earthquake with a magnitude of 7.8 or greater. This lack of data is a particular problem for studies of disaster prevention.

accelerograph sites. A recent detailed investigation of a number of local site conditions, involving borehole investigations, showed that 36 of 50 sites generally reported in the literature as being on rock were in fact on at least 50 ft of alluvium. With so much uncertainty at the accessible end of the transmission path, the difficulty of describing the whole path can be imagined.

Recommendation

Increased efforts should be made to reduce the dispersion in estimates of ground motion parameters at a given site. This will probably involve

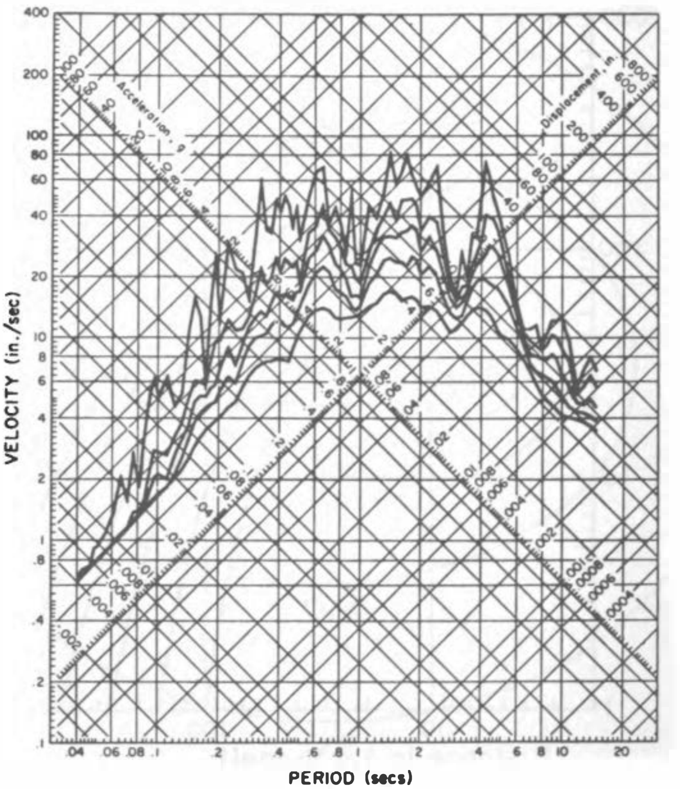


This simplified set of curves illustrates how the intensity of shaking diminishes with distance from the fault for California earthquakes. For example, a peak acceleration of 100 cm/s² (or about 0.1 g) could be produced by a magnitude 5 earthquake at a distance of 12 km, whereas a magnitude 8.5 event could produce the same acceleration at a distance of 200 km. The magnitude 8.5 earthquake would have much stronger long-period components of motion and much longer duration than the magnitude 5 earthquake, and therefore a greater potential for damage. At close distances the shaking is influenced by the details of the faulting process.

the introduction of additional parameters to describe details of the earthquake source mechanism and transmission path, requiring major programs of theoretical investigations and field measurements.

Strong-Motion Data and Design

Earthquake engineers who develop earthquake-resistant designs must somehow translate the measurements of ground motions from field instruments and laboratory analyses into quantities directly related to the destructive effects of earthquakes on structures. An accurate measure of seismic destructiveness has so far eluded earthquake engineers, despite many notable attempts. Such a measure is, of



This response spectrum, calculated from the north-south ground acceleration recorded at the Holiday Inn during the 1971 San Fernando, California, earthquake, shows how effective the motion is in vibrating structures. The values in the graph are the maximum acceleration, maximum velocity, and maximum displacement of a simple vibrating system of specified period of vibration if subjected to the ground motion. (The curves are for 0, 0.02, 0.05, 0.1, and 0.2 fraction of critical damping.)

course, a key step in approaching a major goal for earthquake engineers—the selection of an earthquake ground motion appropriate for design.

A wide range of quantities have been suggested and examined for this purpose: (1) peak values of ground acceleration, velocity, or displacement, (2) modification of such peak values, defining various ‘‘effective’’ peaks, (3) various ordinates or limiting values of frequency spectrum curves, (4) areas under response spectrum curves for selected parameters, (5) root-mean-square ground acceleration, or spectral density, and (6) quantities of the above type combined with the duration of strong ground shaking, defined in various ways. General agreement now exists that no one number can be expected to characterize damage phenomena of such complexity satisfactorily, and attention is turning to various combinations of parameters. A basic difficulty is the complete absence of actual tests to collapse or failure of full-scale civil engineering structures. This makes it very difficult to assess such factors as the deterioration caused by repeated loads, and hence to bring the effects of duration into the picture.

Developing suitable measures of seismic destructiveness is the most important problem in earthquake ground motion now facing earthquake engineers. Solving this problem will require not only a more thorough study of existing ground motion data but also a much more detailed knowledge of how earthquakes damage structures. Progress in this second phase of the subject will call for many more laboratory investigations, analytical studies of the nonlinear response of structures, and detailed studies of the effects of earthquakes on actual structures, involving measurements of structural response during destructive earthquakes. For this reason the inclusion of instrumented structures in the strong-motion networks of the world is of key importance. Recent advances in the subject of ''systems identification'' have facilitated the interpretation of such structural records. This procedure seeks to identify and analyze structural models using input and output measurements made at discrete points in a structural system.

Recommendation

Major efforts are needed to relate measured earthquake ground motion parameters to structural damage in the critical range approaching complete failure. Using measured quantities to define a ''damage parameter'' that would correlate well with earthquake damage would be a major step forward in earthquake engineering.

Management of the Strong-Motion Data Acquisition Program

The details of the organization, management, and operation of various strong-motion networks in the world have varied greatly from country to country. The interchange of information has mainly resulted from many informal arrangements between key individuals. This has been an effective process in the past, but it will certainly encounter increasing difficulties in the future, as the number of stations in the world increases and as new generations of researchers enter the field. The IAEE's International Strong Motion Arrays Council should be an important force in anticipating and dealing with some of these future problems.

In the United States the basic organizational structure that has slowly evolved over the 50 years of the program, which has been highly informal, now faces a number of inevitable changes. In the past the program has depended on an effective but ill-defined cooperation between government organizations, university research groups, and professional engineering organizations. Current social and economic forces are altering the traditional patterns of cooperation between these three elements. If the past successes of the program are to be continued and expanded, as they must be for the health of all earthquake engineering, the entire earthquake engineering community must guide these changes through thoughtful consideration.

A top priority for earthquake engineers in the United States is thus to review carefully the organization and funding of the strong-motion instrumentation program and to set realistic goals and procedures that can be agreed upon by all concerned. The impulse for such an exercise must come from the earthquake engineering community itself, and this group must expect to play an active and continuing role in the whole program. The U.S. National Workshop on Strong-Motion Earthquake Instrumentation in 1981 addressed these matters in some detail, and the workshop proceedings contain a number of significant recommendations that could initiate effective action if implemented.

Recommendation

Because major changes can be expected in the organization, management, and funding of the strong-motion instrumentation program in the United States, earthquake engineers should undertake a comprehensive study of management and funding problems, with a view of formulating specific recommendations for action.

Strong-Motion Seismology

In addition to the developments summarized above in collecting and analyzing basic strong-motion data from the standpoint of the earthquake engineer, the very active research programs of seismologists, geophysicists, and geologists have brought major advances in the theoretical aspects of the subject over the past decade. The increasing availability of near-field ground motion measurements close to the source of seismic energy release has provided strong incentives to study source mechanisms for earthquakes and to increase research on all aspects of the generation and transmission of earthquake waves.

Within a year after the installation of the Parkfield ground motion array mentioned above, a strong earthquake on the San Andreas fault occurred virtually at the center of the array, giving an excellent set of near-field records. This first recording of ground motion in the immediate vicinity of a fault aroused great interest among seismologists and geophysicists, who recognized the value of these measurements for investigating basic fault mechanics. More than 20 papers were published that used these strong-motion records to study the rupture process of the Parkfield earthquake.

This resurgence of interest in basic problems of earthquake mechanics has taken the form of a variety of attempts to model and parameterize earthquake rupture processes while fully exploiting modern advances in computing techniques. At first, simulations of strong motion had to assume an overly simplified earth model, but now more realistic crustal structures, including sedimentary layers, can be handled within reasonable computer time limits. In the meantime, several more earthquakes, including Borrego Mountain in 1968, San Fernando in 1971, Oroville in 1975, Coyote Lake in 1979, and Imperial Valley in 1979, have produced high-quality strong-motion records, and numerous modeling and simulation studies of these have been made.

These studies have boosted the confidence of investigators in trying to estimate strong ground motion from a basic understanding of fault mechanics. Now a major goal is to extrapolate the results from these moderate-sized earthquakes to estimate ground motion for major earthquakes. Researchers would also like to learn how to apply the results from these California earthquakes to earthquakes elsewhere in the country and the world. Recent work on measuring the attenuation of high-frequency seismic waves throughout the United States may help answer this question.

Recommendation

Basic information about earthquake source mechanisms and seismic wave propagation, while of value to earthquake engineering, must be developed mainly by seismological and geological research. The U.S. programs in seismology and earthquake geology should accept the responsibility for funding vigorous programs of research on these important subjects.

Fault Mechanics and Source Parameters

By the end of the 1960s researchers widely agreed that an earthquake results from a slip dislocation, that is, a discontinuous displacement across a fault plane. The slip is, in general, a function of time and location on the fault plane. Once this slip function is given, seismograms can be calculated within a certain frequency band for any observation point, provided that the impulse response for the earth (the so-called Green's function) is known. Various forms of the slip function based on simulations, fracture mechanics, and intuition have been proposed. For example, one of the simplest forms, called Haskell's model, describes a rectangular fault with width W and length L over which a uniform slip, ΔU, takes place. The rupture propagates along the length with a constant velocity, v. The slip at any point on the fault starts to increase linearly with time at the arrival of the rupture front, and stops when the amount of slip reaches ΔU. The time required to complete the slip is called the rise time, T, and is assumed to be the same at every point. Thus five parameters (L, W, ΔU, v, and T) describe Haskell's model completely.

This simple kinematic model has been remarkably useful in representing the gross features of an earthquake source. But various modifications have been proposed to add to the details of the process, including the following: (1) Instead of a unidirectional propagation, a two-dimensional spreading of the rupture front from a nucleation point is assumed, at least in the initial stage. (2) Instead of a uniform slip and constant rise time over the fault plane, a uniform drop in stress over the fault plane is used. (3) Instead of a constant rupture velocity, the propagation of the rupture front is assumed to be controlled by a certain criterion of the fracture. (4) Instead of a uniform strength, a heterogeneous distribution of strength over the fault plane is used.

In the slip dislocation model of an earthquake, one source parameter does not depend on the details of the rupture process. That is the seismic moment, Mo, which equals the final slip integrated over the whole area of the fault plane and multiplied by the medium rigidity, μ. For Haskell's model, $Mo = \mu(\Delta U)LW$. The seismic moment is now widely accepted to be the most fundamental source parameter of an earthquake. It directly measures the extent of faulting and therefore the damage caused by static deformation, including the damage from a tsunami in the case of a submarine earthquake. The seismic moment also particularly interests geologists because it is related to the fault slip and its area, for which there is often direct field evidence.

The seismic moment is proportional to the level of the seismic spectrum at frequencies much lower than the so-called corner frequency of the earthquake (roughly the reciprocal of the duration of the rupture process). On the other hand, the frequency range of strong motion from a large earthquake is usually comparable with or higher than the corner frequency of the earthquake. Therefore the seismic moment may not directly interest engineers, who are concerned mainly with the effects of shaking of typical structures.

The magnitude of an earthquake does not have as simple a physical meaning as does the seismic moment, because it is based on the amplitude of a particular wave measured by a particular seismograph. It is, however, generally believed that M_s (the surface wave magnitude),

M_b (the body wave magnitude), and M_L (the local magnitude) are proportional to the source spectrum at the periods of 20 seconds, 1 second, and less than 1 second, respectively. Therefore, M_b and M_L measure seismic motion in the frequency range of particular interest to engineers. For this reason, M_L, as estimated from strong-motion records by calculating the response of an equivalent Wood-Anderson seismogram, is a useful parameter for earthquake engineering.

The dependence of the seismic source spectrum on the size of the earthquake—that is, the scaling law of seismic spectra—appears to vary from place to place. In particular, the differences between earthquakes at the margins and in the middle of plates seem to be significant, especially in relations between the observed moment and the fault area, the magnitude, and the corner frequency. This difference has to be carefully considered when applying results from California earthquakes to the central and eastern United States.

Recommendation

The significance to engineering of basic earthquake source parameters such as seismic moment and variously defined earthquake magnitudes should be clarified so that earthquake engineers can use them in a consistent way.

Simulation of Strong Motion

The simulation of strong motion in a realistic model of earthquake faulting requires a time-consuming computation. For example, the exact solution for an arbitrary slip dislocation in an arbitrary layered medium is given by a fivefold integral: two over the fault plane, another two over two horizontal wave numbers, and one over frequency. The computer time increases with earthquake size, distance to the observer, and maximum frequency. A present-day computer, for example, can simulate within a reasonable time the strong motion for the great California earthquake of 1857 (using the detailed distribution of slip obtained by a recent geological study) at 1,000 sites throughout California if the frequency range is limited to lower than 0.2 Hz. This is, of course, too limited a frequency range to answer many questions of importance in engineering. To save computer time, various approximate methods (such as mode and ray decompositions) have been used, whenever applicable, to evaluate the fivefold integral. More general models, involving a laterally heterogeneous earth, have also been studied using such methods as finite differences, finite elements, ray methods, integral equation methods, and the Rayleigh ansatz method. A semiempirical approach in which actual seismograms for small earthquakes are used as Green's function to calculate strong motion for a major earthquake has also made some progress.

These simulation methods have been applied to the strong-motion records for several California earthquakes, including Parkfield in 1966, Borrego Mountain in 1968, San Fernando in 1971, Oroville in 1975, Coyote Lake in 1979, and Imperial Valley in 1979. In addition to the strong-motion data, teleseismic body wave data have been used to constrain the modeling. Teleseismic data are particularly useful for comparing the source processes of earthquakes between the eastern and western United States.

One of the main results that have emerged from these studies is that the observed high-frequency motions are much stronger than the motions calculated with a fault model in which stress drops uniformly over the whole area of the fault plane. A heterogeneous drop in stress, nonuniform rupture propagation, or nonuniform slip is needed to explain observed high-frequency motions, so heterogeneities on the fault plane (sometimes called patches, asperities, or barriers) have been postulated.

For frequencies higher than a few hertz, simulation by a deterministic model becomes difficult because specifying the required detail requires too many parameters. To avoid this difficulty, several attempts have been made to introduce a hybrid of deterministic and stochastic models. These models specify gross features of rupture propagation deterministically and consider detailed ruptures to take place randomly in a manner specified by a few statistical parameters. The results of this approach have been encouraging. The parameters used to specify stochastic models, such as the average local stress drop (within a barrier interval) and the cutoff frequency (sometimes called f_{max}), have been remarkably stable for the moderate-sized California earthquakes studied so far.

Recommendation

Simulations of strong ground motion over the frequency range of direct interest to earthquake engineering should be extended, making full use of modern theoretical and computational techniques.

Upper Bounds on Ground Motion: Extrapolation of Data from Moderate-Sized Earthquakes

One of the important problems in strong-motion seismology is to estimate the upper bounds on ground motion for a given site. This difficult task must be shared with geologists. The strategy is to find the maximum possible fault length and width (or depth in the case of a vertical fault) that can break a given section of a mapped active fault. Trenching and other archeoseismological methods can be applied to find the maximum possible amount of fault slip along the section.

Once the expected maximum slip is found, the stability of the local stress drop (discussed in the preceding section) can be used to find the barrier interval or patch size. The stability of the cutoff frequency (f_{max}) allows this parameter to be extrapolated to a large slip. The dependence of the barrier interval and the cutoff frequency on local geology and the mechanical properties of rocks in the fault zone should be studied to estimate these parameters reliably.

Once these parameters (length, width, slip, barrier interval, and cutoff frequency) are known, the time history can be calculated from deterministic modeling for the low-frequency part of strong motion and the power spectrum can be calculated from stochastic modeling for the high-frequency part. As information about the detailed behavior of faults increases, the transition frequency between the two modeling regions can be pushed upward.

Recommendation

Basic studies of the upper bounds of earthquake ground motion are of fundamental importance in evaluating seismic hazards. A combined approach using geological and seismological techniques has been fruitful, and such investigations should be enlarged.

Strong Motion of Eastern U.S. Earthquakes: Inference from the California Earthquake Data

Another important problem in strong-motion seismology is to extend the results from California to estimate strong motion in other parts of the country.

As mentioned previously, the scaling law of seismic spectra may differ between earthquakes at the margins and in the middle of plates, with a higher stress drop possible for the latter. A higher stress drop corresponds to a shorter duration of the rupture process. For example, a teleseismic waveform study found that the Bermuda earthquake of 1978 (which was similar to the Boston earthquake of 1755 in tectonic setting) had a duration of only 3 seconds at the source, which is relatively short for an earthquake with a seismic moment of about 3×10^{25} dyne-cm.

A more distinct difference between eastern and western U.S. earthquakes concerns the attenuation of seismic amplitude with distance. In general, this attenuation is much less for the eastern United States than it is for the western United States. The difference is strong for frequencies around 1 Hz and diminishes with increasing frequency. This means that the frequency dependence of attenuation differs between the two regions. In the western United States attenuation is roughly independent of frequency over an intermediate frequency band. This justifies the frequent practice of using similarly shaped response spectra for California earthquakes regardless of distance. In the eastern United States, on the other hand, higher frequencies attenuate considerably faster than do lower frequencies. Thus similarly shaped response spectra cannot be used at all distances. This effect must be taken into account in applying California response spectra to the eastern United States. As knowledge increases, it may prove that an even more detailed breakdown into smaller regions is possible or necessary to consider the generation and propagation of damaging earthquake waves.

Earthquakes in California and in the eastern and central United States also differ in that many western earthquake faults rupture to the surface, whereas those in the eastern and central states usually do not.

Because of the extremely low attenuation in the eastern United States as compared with California, seismic waves traveling along multiple paths through the heterogeneous lithosphere arrive at an observation site with significant amplitude. This effect tends to make the duration of shaking longer, although the source duration may be shorter in the eastern United States, as mentioned earlier. The unusually long duration (4-1/2 minutes) of the Boston earthquake of 1755 perhaps resulted from this multipath effect. Such an effect is not strong in California, as shown by the relatively short duration (40 seconds) of strong shaking during the San Francisco earthquake of 1906. The latter duration must be attributed to the duration of the rupture process.

Thus a correct understanding of fault mechanics and seismic wave propagation in each region is absolutely essential before the empirical results obtained in one region can be applied to other regions.

Recommendation

Progress has been made in comparing source mechanisms and seismic wave propagation between California and the eastern and central United States. Further studies are needed to gain basic understanding of these subjects, an understanding that is essential to apply results from California to sites in the eastern and central United States.

5

Soil Mechanics and Earth Structures

The effects of earthquakes during recent years and a developing understanding of these effects have demonstrated the great importance of soil mechanics to earthquake engineering. Not only have the foundations of structures lost their support during ground shaking, but soil deposits and earth structures have themselves failed. Examples of such failures include the destructive Turnagain Heights landslide during the great Alaska earthquake of 1964 and the near-catastrophic collapse of the Lower San Fernando Dam during the San Fernando earthquake of 1971. The failure of this earth dam threatened the lives and property of 80,000 residents downstream.

Even when the soil does not fail, it may modify the ground shaking experienced by structures. This was vividly illustrated by the contrast between motions recorded at the Humboldt Bay nuclear power station in 1975. At the base of the station 75 ft underground a maximum acceleration of 0.14 g was recorded, while at the ground surface a maximum acceleration of 0.30 g was recorded.

Great progress has been made in understanding and explaining such behavior and in developing sound concepts and procedures for designing new structures and strengthening existing hazardous facilities. A blend of different research undertakings have produced these advances.

- Careful observation, description, and classification of significant occurrences—ground failures or collapse of dams, for example—during earthquakes and study of their relation to geological and geotechnical settings.
- Fundamental study of the stress-strain behavior of soils during earthquake shaking.
- Development of methods of analysis for a wide variety of problems, making use of the enormous power of computers.
- Improvement of practical methods for evaluating the soil properties required as input to analytical methods.
- Checking and further improving theories of soil mechanics by

This large landslide in the Turnagain Heights suburb of Anchorage, Alaska, destroyed many homes. The magnitude 8.4 Alaska earthquake of 1964 caused many large and damaging landslides because of its prolonged shaking. The shaking in Anchorage was perceptible for 4 minutes.

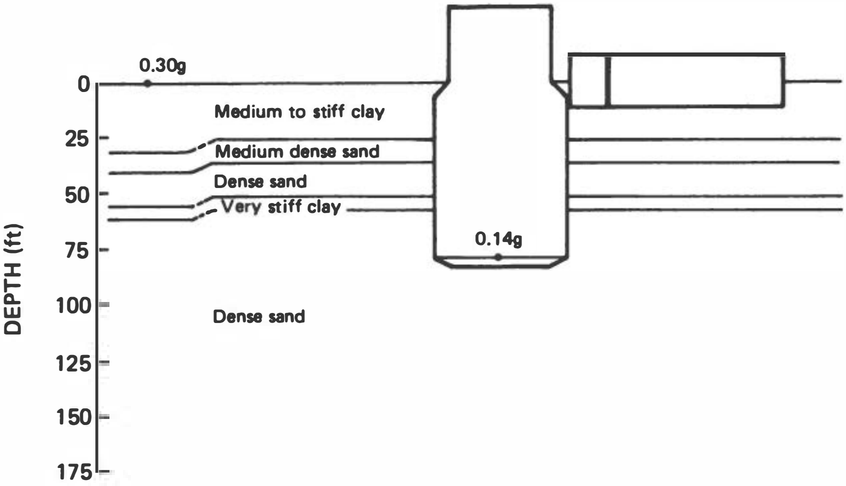
comparing the predicted responses of earth structures and soil deposits with observations and measurements made during actual earthquakes.

The following sections discuss these advances and the important research that remains to be done.

Effect of Local Ground Conditions on Earthquake Motions

Knowledge of the intensity and nature of ground motions is fundamental to sound earthquake engineering design. For some time it has been evident that local ground conditions can have profound effects on earthquake ground motions. Not until the 1970s, however, were these complex phenomena understood well enough for relevant items to be incorporated into building codes and design procedures.

In the simplest terms, local ground conditions can be described as rock or as soil. Generally, the more deformable the site (either in



The maximum accelerations recorded at the Humboldt Bay nuclear power station during the Ferndale, California, earthquake of June 7, 1975, were much greater at the surface of the ground than at the base of the station. This shows how the surrounding soil and soil-structure interaction can modify the ground shaking experienced by structures.

terms of the softness of the soils or the greater thickness of the soil deposit), the greater the difference between ground motions on a rock site and ground motions on a soil site. The soil can either increase or decrease the response of a structure, depending on the type of structure and the dimensions and physical properties of the soil. This is why it has been difficult to develop simple and reliable rules describing the effects of site conditions.

The present-day understanding of the important characteristics of earthquake motions and of how local ground conditions affect these characteristics has come from two sources: (1) recordings obtained during earthquakes over the past four decades (and, in particular, over the past 12 years) and (2) theoretical considerations and analytical studies based on research conducted over the past two decades. Some analytical procedures that were developed late in the 1960s have been significantly improved in the past decade by research, especially by the opportunity to compare predicted motions with actual recordings of earthquake motions. More recently, analytical procedures based on the propagation of seismic waves from the earthquake source to the site have been developed. These latter procedures have not yet reached the point of practical application.

Today it is common practice to evolve site-specific ground motions to use in designing very important facilities such as nuclear reactors. This is done by careful selection from existing records, guided and supplemented by analytical methods. The results of research and experience have also been incorporated into the present edition of the Uniform Building Code and into the *Tentative Provisions for the Development of Seismic Regulations for Buildings* prepared by the Applied Technology Council (ATC). These steps have resulted in safer designs, and in some cases in more economical facilities.

The recorded data cannot yet fully reveal all the parameters that are believed to influence earthquake motions. Therefore there is a great need to continue and to expand the recording networks in seismic regions. Better instrumental coverage will increase the data base and provide significantly improved means for assessing, isolating, and understanding the effects of local ground conditions on earthquake motions, thus improving seismic design criteria. Most existing recording instruments provide data at or near the ground surface, but recorded earthquake motions at various depths are also urgently needed. Downhole instrument arrays, such as those used in Japan, can most readily meet this need. Future effort will also be required to evaluate the nonlinear soil effects that influence earthquake motions, particularly for sites underlain by relatively soft sediments such as exist in many offshore areas. It is harder to evaluate the long-period components of ground motions than it is for the shorter-period components. Such long-period motions are particularly important for some structures (such as high-rise buildings, offshore platforms, large tanks, and high dams), and more accurate procedures need to be developed.

Soil-Structure Interaction

The phrase ‘‘soil-structure interaction’’ refers both to the influence of a structure on ground motions that occur in its vicinity and to the influence of adjacent soil on the dynamic response of a structure. Because of its importance in the seismic design of nuclear power plants, soil-structure interaction during earthquakes has received much attention during the past decade. The research done has contributed to a greater insight into the phenomenon and to an understanding of the factors that influence the interaction. Among these are embedment of the structure, the nature of the ground motions (whether they result from surface waves or body waves), the wave lengths of the ground motions, nonlinear effects within the soil, and in some instances nonlinear effects at the interface between the structure and the soil.

Various sophisticated computer programs have been developed to include the effects of soil-structure interactions in the dynamic analysis of a structure. One reason for the variety of programs is that the choice of an analytical model for a structure affects the choice of a model for the soil, and vice versa; this matter is touched upon again in Chapter

6. When done in a consistent manner, the several procedures give similar results. A key to this consistency is in specifying the seismic input to the structure. Consequently, understanding and defining the lateral and vertical variation of the ground motion is a key element in studies of soil-structure interaction. To date there has been a lack of recorded data from instruments located so as to provide this information. Arrays of instruments should be installed at selected sites to provide data in this important area.

The currently used analytical procedures have been developed for massive mat-supported structures constructed on (or embedded into) relatively competent rock and firm soil, typical conditions for nuclear plants. The procedures have been checked against the limited data available from actual earthquakes and have been found to provide reasonably good predictions. For ordinary buildings a simplified method, which has been included in the ATC provisions, appears to be adequate. For special structures and foundations, such as offshore platforms, tall towers, long-span bridges, pile foundations, and very soft soils, the situation is not yet satisfactory and further research is needed. Nonlinear soil effects, and in some cases nonlinear structural effects, can be important, and both require further work. Although the vibrating interaction of adjacent structures has received some study, this problem also calls for more research.

Soil Liquefaction During Earthquakes

During earthquakes a statically stable sandy soil can become liquefied or semiliquefied, losing its ability to support a structure or remain in place on a slope. Accounts of earthquakes over the past 2,000 years contain evidence of soil liquefaction, but not until the extensive occurrence of this phenomenon in the Alaska and Niigata, Japan, earthquakes of 1964 did the scientific and engineering communities fully appreciate its potentially catastrophic consequences. The result was a major effort to provide the capability of determining which soil deposits can be expected to liquefy under different intensities of earthquake shaking. There have been two parallel and often overlapping lines of investigation, one aimed at understanding the underlying basic phenomena—intergranular movements, etc.—and the other aimed at developing practical procedures for use in analyzing specific sites.

The early evaluation procedures involved a combination of analytical and experimental techniques, the success of which depended largely on the ability of the engineer to test samples of soil under conditions similar to those in situ. The large number of laboratory investigations clearly showed that liquefaction occurs only in cohesionless soils

The foundations of these apartment buildings failed due to liquefaction in the Niigata, Japan, earthquake of 1964. These reinforced concrete buildings survived without structural damage despite settling into the ground and in some cases tilting. A strong-motion accelerograph recorded the shaking on the ground floor of one of these buildings, and it showed that the acceleration did not exceed 0.1 g, which is only moderately strong ground shaking.

(usually sands and silty sands) and that even small quantities of clay inhibit the increased pore water pressure that is required in liquefaction. A major benefit of these laboratory studies was the recognition of the many factors that determine the liquefiability of a given sand deposit. Research has produced a large body of information in recent years that has resulted in a good understanding of the physical processes leading to liquefaction and in a better appreciation of the difficulties in applying the laboratory-based evaluation procedures.

While these basic experimental and analytical studies were in progress, concerted efforts were also made to identify case studies where liquefaction did or did not occur during earthquakes. Such studies have been obtained from many different countries, including the United States, Japan, China, Argentina, and Guatemala, and over 200 case histories now form the basis of empirical procedures for evaluating the resistance to liquefaction at different sites. The framework for these procedures evolved from the earlier analytical approaches, but they are based on a relationship between certain in situ properties of sands (usually the penetration resistance) and the observed performance of many deposits in many earthquakes. The extensive data from these earthquakes have provided a reasonable basis for practical methods now used in design.

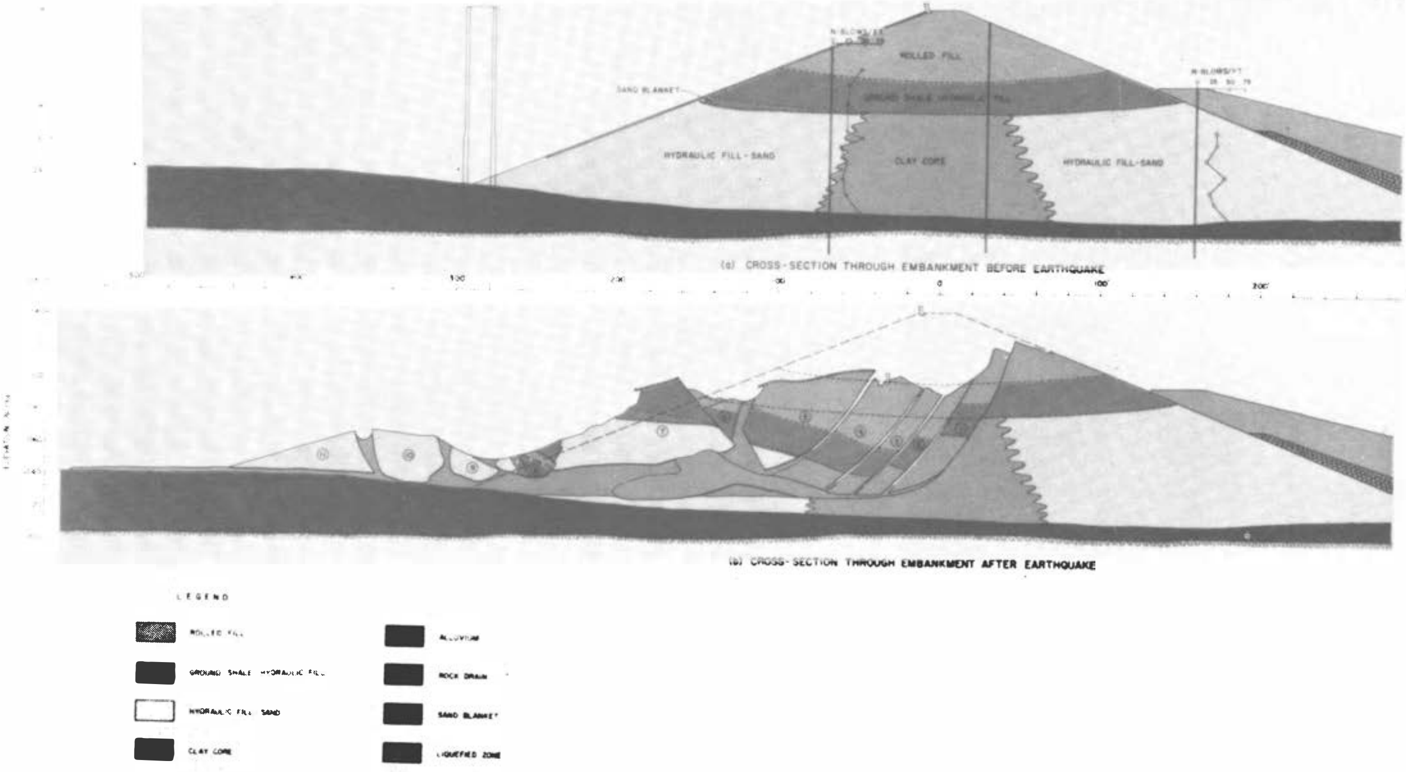
As noted earlier, an important feature of liquefaction is the building up and dissipation of pore water pressure during an earthquake. Research into this phenomenon has had broad applications. For instance, the analytical procedures developed can now be used to understand the behavior of coarser ground deposits, such as gravels or rockfills. They can also be used to develop drainage schemes that can prevent liquefaction by dissipating pore water pressures as rapidly as earthquake shaking can generate them.

Thus a period of intensive research, mainly in the United States and Japan, has been very effective in building up the scientific and engineering understanding of liquefaction, leading to useful methods for evaluating the liquefaction potential of sand deposits. It has also led to methods for mitigating the hazards associated with this phenomenon, thus providing for increased public safety and welfare through avoidance of loss of life and prevention of extensive damage to structures.

Despite the progress that has been made toward solving the liquefaction problem, additional research is needed, especially concerning the generation and dissipation of pore water pressures and the transient and permanent deformations associated with liquefaction. It is particularly important to observe and measure these aspects of responses during actual earthquakes. Research sould also consider the liquefaction of soils other than sand, such as silts, silty sands, and deposits containing cobbles and boulders. A further effort should be made to increase the precision of methods of predicting liquefaction. On a very practical level, research is needed leading to standardization of the so-called standard penetration test and to improved techniques for in situ investigation.

Earth Dams

Not until the mid-1960s did significant interest develop in the possibility of earthquake-induced failures of earth dams. While several dams were known to have failed as a result of earthquake shaking, the prevailing view prior to this time held that these dams failed because of poor construction and that well-constructed earth dams designed by existing static methods were adequately resistant to earthquakes. However, as earth dams were constructed to increasing heights in the 1960s, design and regulatory agencies became concerned about seismic stability, and research on the problem was initiated. Important progress resulted, but the near failure of the Lower San Fernando Dam in 1971 finally convinced the engineering profession of the urgent need for improved design procedures. The earthquake damage lowered the height of the dam so that only 4 to 5 ft of badly cracked earth remained above the



Cross section through the failed Lower San Fernando Dam. SOURCE: H. Bolton Seed, 1975, "The Slides in the San Fernando Dams During the Earthquake of February 9, 1971," *Journal of the Geotechnical Engineering Division* 101(July):674.

water level. Many feared that a strong aftershock might release the water in the reservoir; people living downstream of the dam were ordered to evacuate, and steps were taken to lower the water surface to a safe level as rapidly as possible. This was accomplished without any further sliding of the portion of the dam that remained standing. However, the margin by which a major disaster was avoided was uncomfortably small.

This event triggered a major program of research and investigation into earthquake-resistant design procedures for earth dams. Significant progress had already resulted from the development of cyclic loading tests to simulate earthquake effects on soil samples, the development of finite element analysis procedures to determine the response of structures to earthquake motions, and the development of analytical approaches to evaluate the stability of embankments during earthquakes. A comprehensive investigation was made of the sliding that took place during the failure of the Lower San Fernando Dam. This was followed by research on the dynamic response of the dam, and recommendations were made for improved seismic safety evaluations. As a result, new methods of evaluating seismic stability were adopted by the U.S. Army Corps of Engineers, the Bureau of Reclamation, the Tennessee Valley Authority, the Federal Energy Regulatory Commission, the State of California Division of Safety of Dams, and many other government and private engineering organizations throughout the world. Application of these advances has led to the replacement of some old hazardous dams and the strengthening of a number of weak dams, with a corresponding increase in public safety. However, the problems posed by existing dams that would be unsafe in the event of an earthquake are not yet completely solved.

Other research, both experimental and analytical, has investigated the behavior of dams during earthquakes, including studies to relate performance to design and construction procedures. This research has established that certain types of cohesionless soils are extremely susceptible to loss of strength during earthquake shaking, while other soils, such as moist sands and gravels or clays, show negligible reductions in strength and retain high levels of seismic stability. Progressive improvements in analysis techniques in recent years have yielded methods to estimate the permanent deformations of earth dams due to earthquake shaking, predict the changes in pore water pressure within the body of the dam, and assess postearthquake stability. As a result of these and related studies in geotechnical engineering, practical and simplified methods of evaluating seismic stability are now available.

While much has been accomplished, much remains to be learned before the dual requirements of safety and economy can be achieved in these critical structures. Current methods of analysis need to be refined, and there is a need for improved procedures to evaluate the deformation of earth dams during earthquakes. Better information should be sought on how induced pore pressures are dissipated, what the associated deformations are, how stable dams are after shaking and with respect to aftershocks, and how highly nonuniform natural deposits behave in dam foundations.

Retaining Structures, Tunnels, and Pipelines

Retaining walls that hold back earth, quay walls in harbors, and bridge abutments have been frequently damaged by strong earthquake ground shaking, with considerable economic losses and disruption of transportation. Through research, a new and more rational approach to the design of gravity retaining structures has been developed, based on the principle of limiting movement rather than avoiding overstressing. This procedure has been incorporated into the new *Seismic Design Guidelines for Highway Bridges*, which the American Association of State Highway and Transportation Officials is now considering for adoption.

Advances have also been made in the methods available for computing dynamic earth stresses against rigid structures, so as to permit more rational design of, for example, basement walls for large buildings. Other research has established the basis for seismic design rules for reinforced earth-retaining structures.

As experiences during earthquakes have accumulated over the past decade, it has become clear that deep tunnels are usually little affected by an earthquake, unless, of course, they pass through a zone of fault movement. Shallow tunnels can experience damaging movements, especially the opening of joints between sections. Methods have been developed to determine the amount of motion that must be tolerated at joints, allowing the necessary seals to be designed. This work also applies to buried pipelines. While earthquake-induced stresses in continuous pipes are usually not of overriding concern, methods for computing these stresses have been developed to take them into account in design.

Major damage can occur when a tunnel or pipeline crosses a fault that displaces during an earthquake. Novel concepts have been developed to minimize the likelihood of such damage, especially for buried pipelines, along with analytical procedures for the rational design of fault crossings. Such techniques have been applied, for example, to the Alaska oil pipeline.

Another major threat to pipelines is slumping or sliding of ground through which they pass. At present there are no economical methods

This water hydrant was shattered by the high water pressures generated during the 1971 San Fernando, California, earthquake. The pressures were presumably the result of underground deformations of pipes caused by soil strains. Such damage to the water supply system makes a community vulnerable to uncontrolled fires.

(other than relocation) for reducing this threat, and research into this problem is needed.

Many of the developments mentioned in this section have taken place during the last few years. Although they have found their way into practice for specific projects, they need to be verified experimentally and the disparate developments need to be brought together into a coherent body of practice. Particularly needed are additional data from specially designed arrays of strong-motion instruments to reveal relative movements during earthquakes between points in the earth separated by from 100 to several thousand feet.

Stability of Slopes

Aside from slope failures associated with liquefaction, landslides, rock falls, and avalanches are common features of a major earthquake in mountainous or hilly terrain. Such occurrences have caused deaths, destroyed buildings, blocked routes of transportation, dammed streams, and in exceptional cases destroyed entire cities. Where a particular slope is identified as being of concern, and where the expense of detailed geological and geotechnical investigation is warranted, the analytical tools used to study earth dams can be similarly used to assess the safety of a slope and design remedial works. However, the problem is generally regional, where so many slopes might be susceptible to earthquake-triggered sliding that they cannot all be individually analyzed. Geologists and geotechnical engineers of the U.S. Geological Survey have developed techniques for mapping areas most likely to be hazardous because of earthquake-triggered earth movements, and such maps are a valuable tool for regional planning. Intensive studies should be made of significant landslides with the objective of improving the ability to assess the earthquake resistance of natural slopes.

Understanding and Evaluating Soil Properties

Soil, as an engineering material, is extremely complex. The particles that make up soil have widely differing sizes, shapes, and physical properties. Furthermore, the physical properties of the soil medium depend on such things as the origin of the particles, the manner of

A large landslide during the 1964 Alaska earthquake caused extensive damage to these commercial buildings on Fourth Avenue. Research has done much to clarify the mechanism of such slides, but more needs to be done on assessing the potential for slides.

deposition, the age of the soil deposit, the pressures to which the soil was subjected in the past, the amount of moisture in the soil, and the state of stress existing in the soil. It is not possible, therefore, to generalize about soil properties. Each particular soil deposit is, rather, a unique material whose properties must be determined before engineering can proceed.

The advances described in the preceding sections have been possible only because of the significant progress in two areas: understanding the stress-strain behavior of soil when subjected to earthquake motions, and developing reliable methods for evaluating the parameters required in analytical methods. Basic research on dynamic soil behavior during the past 20 years has provided the foundations for this progress, and the recent decade has seen major developments in putting this research into practice.

Because of the complex nonlinear behavior of soils when subjected to stress, idealized stress-strain relations adapted to the particular problem under consideration generally have to be used. Three types of problems can be distinguished.

1. Evaluation of Modulus and Damping In some situations only the transient seismic response of soils is of concern, and then it is usually sufficient to model the soil as a "linear" material with modulus and damping adjusted for the level of strain predicted by the calculations. These situations include such problems as the effect of local soil conditions on earthquake ground motions and the interaction between a structure and the supporting or surrounding soil. Even when failure or large permanent deformations must be considered, the overall study often includes a "linear" response analysis. Thus one very important practical problem is to evaluate the modulus and damping of soil as a function of the level of strain. Determining the stiffness and damping of soils throughout the range of shearing strains of interest usually requires two steps. First, in situ seismic methods, which develop only small shearing strains, determine the soil stiffness at the proposed site. Then laboratory tests on representative samples from the site establish the stiffness and damping for large-amplitude shearing strains. Customarily, the soil stiffness is given in terms of the shear modulus, which is closely related to the propagation velocity of shear waves through the soil.

Several geophysical methods of investigation are in use today, but cross-hole tests are the most versatile. In this method, energy is imparted to the soil at some depth in a borehole, and the arrival of this energy is detected at the same depth in nearby bore holes. Recent improvements in this method include the development of reversible impact mechanical hammers that can act in cased boreholes, techniques for ensuring positive contact of pickups against the casing, and improved methods and instrumentation for signal enhancement. With present techniques the shear wave velocity can be identified in a particular soil layer with much greater accuracy than was possible a decade ago. The conventional geophysical methods produce only small-amplitude shearing strains in the soil, but a few research-type studies have achieved earthquake-level shearing strains. Further research should be done to develop methods of inducing large strains that can lead to practical applications. Research should also be done on methods of determining in situ soil damping as a function of shear strains induced by stress waves.

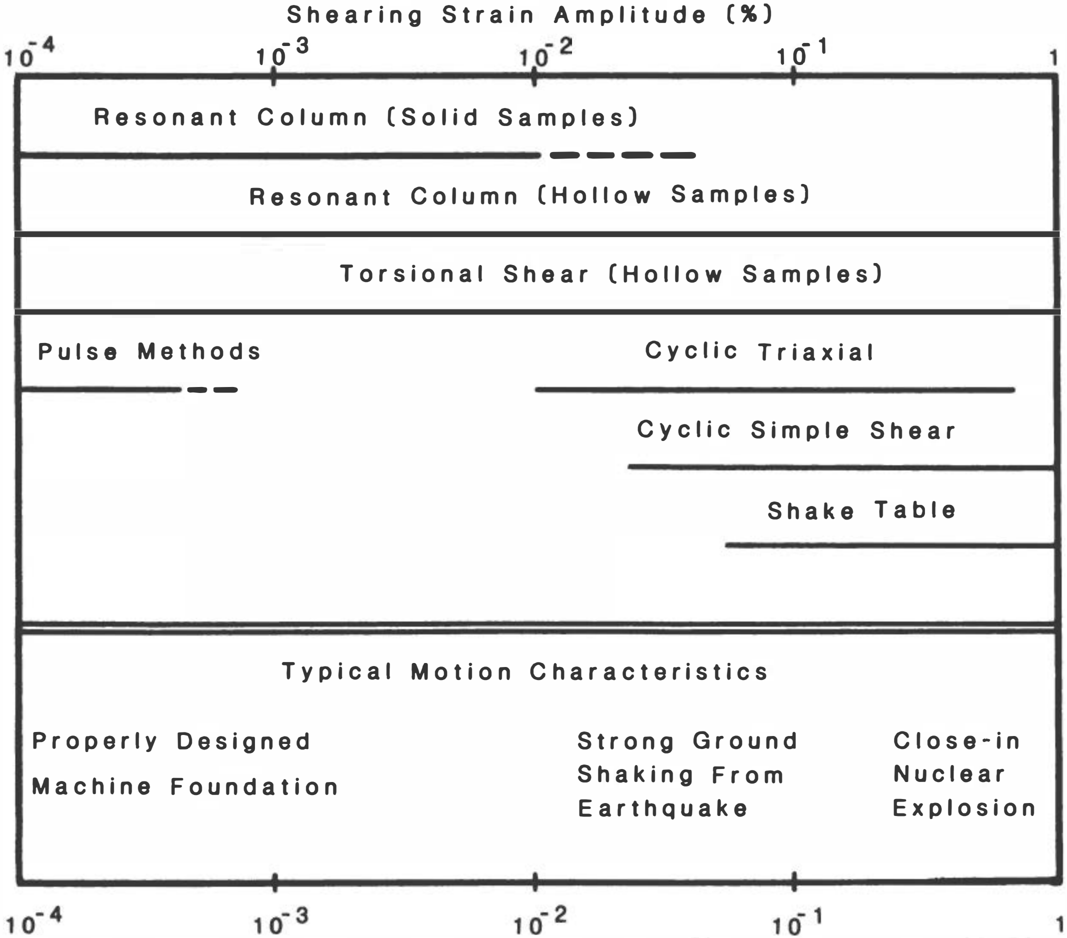
A variety of tests have been developed for measuring soil rigidity and damping in the laboratory. Resonant column tests, which can be used to evaluate modulus and damping for strains ranging from those used in geophysical tests in situ to those encountered during earthquakes, can now be performed by more than 70 engineering laboratories in at least 14 different countries. Torsional tests on hollow cylinders of soil can give data for even larger strains, but such tests are still primarily a research tool, as are other forms of testing.

The stiffness and damping of clean, cohesionless soils depend primarily on the density of the soil and the confining stress that acts upon it. Evaluation techniques applicable to these soils have been developed and checked during the past dozen years, and these methods have been adopted in practice.

Many factors, some arising from the sampling and laboratory testing procedures, influence the behavior of cohesive soil. During the past decade research concerning time effects has helped explain the differences found between field and laboratory soil stiffnesses at low strain amplitudes, and at larger strains significant progress has been made in identifying how shearing strain amplitude and the number of repetitions of straining influence test results.

Continued research on the effects of strain history is needed for natural cohesive soils and cohesionless soils containing silt-sized particles on one hand or gravel and cobbles on the other. Where significant pore pressures develop during cyclic loading, more work is required to evaluate the resultant reduction of soil stiffness. Cumulative changes in stiffness and damping during seismic stressing need intensive study, as does the effect of such stressing on subsequent strength.

2. Evaluation of Permanent Deformations Many problems in soil mechanics, such as safety studies of earth dams, require that the possible permanent deformations that would be produced by earthquake shaking of prescribed intensity and duration be evaluated. Where failure develops along well-defined failure planes, relatively simple



Laboratory apparatus have a range of shearing strain amplitude capabilities over which they give useful information.

elastoplastic models may suffice to calculate displacements. However, if the permanent deformations are distributed throughout the soil, the problem is much more complex, and practical, reliable methods of analysis are not available. Future progress will depend on development of suitable plasticity models for soil undergoing repetitive loading. This is currently an important area of research.

3. Liquefaction The earlier discussion of liquefaction emphasized the important role of laboratory experiments in developing a basic understanding of the physical phenomenon. Because the soils most susceptible to liquefaction are also most affected by sampling disturbance, in situ penetration tests are commonly used to evaluate resistance to liquefaction. However, such penetration testing has suffered from a lack of standardization and cannot be used for soils containing gravel or cobbles. Research has recently turned to this problem, leading to the use of in situ measured shear wave velocity as an alternative for evaluating liquefaction resistance. Also, freezing techniques have been found to reduce the effects of sampling disturbance.

The Future

A comparison of the present state of soil dynamics with that described in the 1969 report *Earthquake Engineering Research* shows how far knowledge of soil dynamics problems has advanced. It also shows the research that remains to be done. Some new problems have come to light, the emphasis on aspects of old ones has changed, and some new equipment and techniques are available.

Despite the enormous increase in information on soil response provided by the 1971 San Fernando earthquake and the 1979 Imperial Valley earthquake, recorded data on ground motions in different soils is still needed, especially in the most strongly shaken regions of larger earthquakes. Data on ground motion as a function of depth in soil are still lacking, since too few sites have vertical arrays of seismometers installed in boreholes. To be of real value, such data must be accompanied by reliable information on the properties of the soil at various depths in the vicinity of the seismometers. Such field studies should be carried out wherever instrument arrays are installed.

The continued development and extension of computerized numerical methods have improved design analyses and procedures substantially in the past decade, particularly with regard to the analysis of ground motion and soil-structure interaction at specific sites. However, the soil models have for the most part remained relatively unsophisticated, and the developments in complex static soil models have impinged little, so far, on dynamic research. More research on the dynamic constitutive behavior of soils is needed. While a good fundamental understanding of the liquefaction process has been achieved, more work remains before the phenomena can be predicted in detail. Some of the laboratory apparatus of a decade ago has been refined and improved, but standardized tests and equipment are still lacking, and more refined experimental procedures should be developed to investigate complex strain conditions. Studying the effect of cyclic stressing on the subsequent strength of soils will be especially important.

Even more important than the development of new experimental equipment is the need to upgrade and modernize university laboratory equipment. Most laboratories in the United States work with outdated apparatus, and many lack modern data acquisition and processing equipment. This is in sharp contrast to European and, especially, Japanese laboratories.

There is a great need for detailed information on the behavior of full-scale structures and their foundations during actual earthquakes. Also, with the increasing availability of analytical and laboratory test procedures, research should seek to determine the suitability of these analyses for predicting field performance. To this end, more full-scale structures should be instrumented and relevant material properties should be determined. Analyses of the response of structures and foundations should be made whenever the opportunity presents itself. Such studies are essential to boost confidence in analysis and design procedures. However, getting data for such studies depends on the coincidence of strong earthquake shaking near instrumented structures.

Alternatively, the usefulness of theories can be assessed by observing the behavior of smaller-scale structures in laboratory tests. More advantage should be taken of earthquake shaking table tests, provided appropriate care is exercised in determining the properties of the soils used in the tests at low confining pressures. In recent years the development of centrifuge technology has overcome this need to scale soil properties, and this technology holds promise for important developments in the next decade. A centrifuge can test scaled structural models including soil, with linear dimensions from 1/20 to 1/200 of those of the prototype, under accelerations that cause stresses, strains, and pore pressures in the soil similar to those in the prototype. Geotechnical centrifuge research in the 1970s has largely emphasized static soil-structure performance, and relatively few dynamic tests have been performed. However, a number of shaking devices and earthquake simulators for centrifuge research have been developed. Additional fundamental research should be done on soil dynamics in the centrifuge.

Ideally, centrifuge research should be correlated with observations of full-scale dynamic behavior. In the absence of earthquakes, man-made excitation could produce the shaking of prototype structures. For example, preliminary trials of reusable in-ground explosive techniques for exciting adjacent structures have shown promise, and further development should be pursued.

Some structures that were only being developed 10 years ago have assumed importance in recent years—in particular, the very large offshore oil-drilling platform, of steel or concrete, in water 300 to 400 m deep. With piles 150 m long and correspondingly large in diameter, and with concrete platform bases 100 m or more in diameter, full-scale static or dynamic tests appear impossible. In recent years, such structures have been evaluated by analytical methods alone. Evaluations of their field behavior under dynamic wave or earthquake conditions have not progressed well or, perhaps, have been kept confidential by the oil companies. Offshore platforms also place great demands on techniques of offshore soil investigation and on the understanding of the behavior of ocean-floor soils. For a variety of offshore applications, improved field investigation techniques and laboratory research on these soils are urgently needed.

New or improved methods of in-place testing of soils, both statically and, especially, dynamically, need to be developed. It is important that test methods be capable of subjecting the soil to large strains, at least as large as those generated by ground motions or by soil-structure interaction during earthquakes. Much of today's knowledge of dynamic soil behavior comes from laboratory tests on remolded or very substantially disturbed soils; this needs to be supplemented by field tests.

In summary, the areas of soil dynamics research in which effort should be concentrated in the next decade are (1) installation of arrays of instruments to record spatial variations in earthquake motions; (2) field tests of full-scale structures (or very large models); (3) centrifuge studies of correctly scaled models; (4) in-place dynamic field tests; (5) development of improved dynamic laboratory tests; (6) further development of dynamic constitutive soil models; (7) increased understanding of soil behavior during and following earthquakes; (8) continued work on the problems peculiar to soil-structure interaction; and (9) programs of structural and site instrumentation. Analytical targets-of-opportunity will continue to arise as earthquakes shake instrumented and uninstrumented structures of interest, and full advantage should be taken of all such opportunities. Since major earthquakes occur infrequently, this need will continue well into the future. Finally, upgrading of university laboratory equipment and installation of data acquisition and processing systems are essential to underpin all of these efforts.

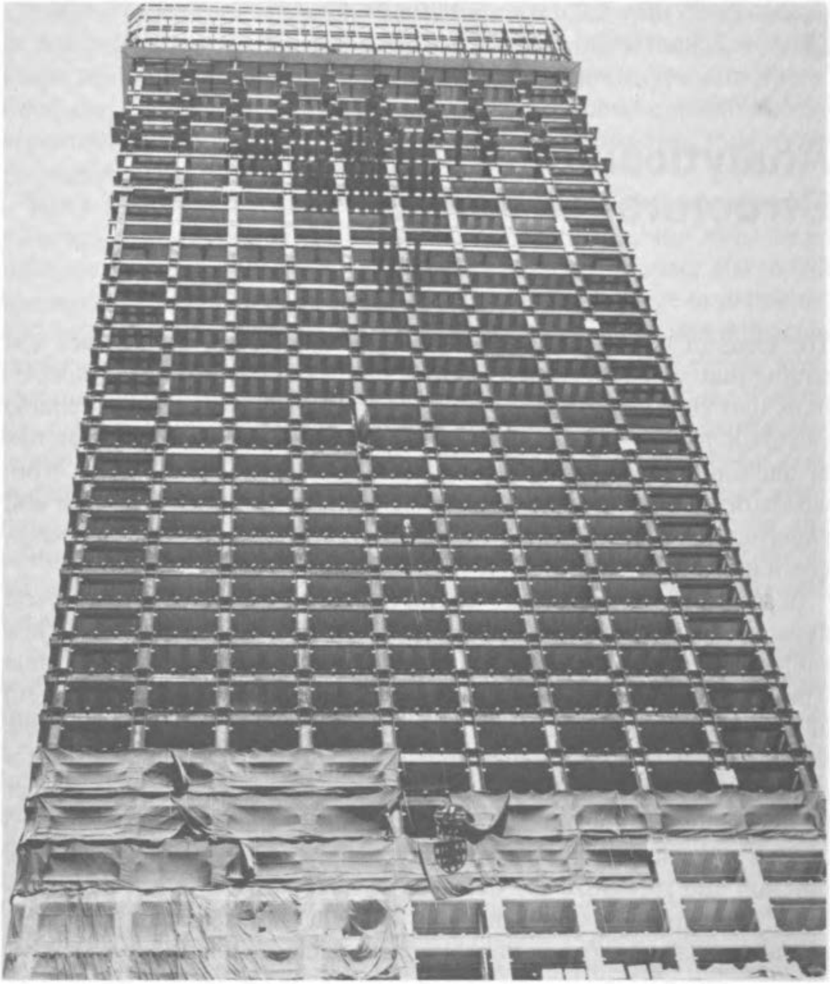
6

Analytical and Experimental Structural Dynamics

The basis of all structural engineering is the analysis of stresses and strains that specified forces produce in structures. It is these calculations that guide the design of a structure. The ability to make reliable calculations of this type requires a knowledge of the physical properties of building materials and structural elements. This must come from laboratory experiments and full-scale testing. Analytical research and experimental research must both be done to develop structural engineering properly.

In the field of earthquake engineering, the objective of structural dynamics is to predict the performance of man-made structures when subjected to strong earthquake motions. The analyst must determine whether maximum stresses in the structure will exceed the strength of the building materials and thereby initiate damage and possible failure. Similarly, the analyst must estimate the maximum displacements induced in the structure by the earthquake to determine whether it can continue to perform its function during and after the event. To do this the analyst must thoroughly understand the structure's total function and recognize the detrimental effects that stresses or deflections can have on that function. Thus it is evident that dynamic response analyses provide a necessary guidance for designers, serve to verify the adequacy of proposed designs, and are a basic ingredient of seismic safety studies for existing structures.

The essential prerequisite to any analysis of earthquake response is a comprehensive mathematical description of the ground motions expected at the site of the structure; this subject is discussed in Chapter 4. The first step in performing the analysis is then to formulate a mathematical model that simulates the behavior of the real structure. Not only should the model predict the response behavior in the linear elastic range, but it should also aid in estimating the degree of damage to be expected and the possibility of catastrophic collapse. Therefore the mathematical model must describe the resistance of a structure to a sequence of randomly varying cyclic deformations, while accounting for a significant degradation of stiffness and strength in the structure. The 1969 National Academy of Sciences-National Academy of Engineering report *Earthquake Engineering Research* pointed out that a



The gridwork of steel I-beams and columns in this high-rise building under construction in Los Angeles provides the resistance against earthquake forces. The four sides of the building form a rectangular gridwork, anchored at its base to a heavy concrete foundation. This vertical tube deforms and vibrates under earthquake excitation, and the beams and columns and their intersections must be strong enough to withstand the imposed stresses. The responses of this building to several different earthquake ground motions were calculated on a digital computer, and the building was designed to survive strong ground shaking.

lack of information on the dynamic properties of materials, components, and structural assemblages was a major obstacle to reliable predictions of structural performance. Accordingly, research has emphasized this topic in recent years.

Once a suitable mathematical model has been defined, analyzing a structure's response to a specified ground motion is a standard mathematical problem, and in principle can be solved in many different ways. However, because of the complexity of the models formulated to represent realistic structures, the only practical means to do the analysis are numerical procedures performed by digital computers. Significantly, dynamic analysis capabilities have developed in the past 20 years in parallel with the development of electronic digital computers. Advancements in computer capabilities have made it possible to use increasingly refined models of structural systems, ones based on improved understanding of materials and system properties.

This chapter outlines the major advances made in structural dynamics analysis during the past decade and focuses attention on areas where intensive research is still needed. The first section discusses the many types of response analysis procedures that have proven effective in various situations. A description of the problem of soil-structure interaction follows, including a discussion of techniques for analyzing such combined systems. Although this is really just part of the general topic of analysis methods, it receives special treatment because so much of the work in structural dynamics has dealt with techniques of interaction analysis.

The next sections deal with experimental research aimed at defining mathematical models capable of reliable predictions of response. Laboratory studies on materials, components, and structural models and field experiments on prototype structures are both discussed. In addition, the mathematical procedures for establishing the properties of models from experimental data are discussed; these techniques generally fall under the classification "system identification."

Dynamic Analysis Methods

Analysis of Buildings

Seismic analyses of most buildings of simple and regular shapes still use equivalent static lateral loads whose amplitude depends on a seismic coefficient specified by the building code. In the last 10 years, however, the use of dynamic analyses, both linear and nonlinear, has increased substantially, not only for special structures such as nuclear power plants or offshore platforms but also for other important buildings. Major factors in this development have been the increasing number of engineers, educated in earthquake engineering and structural dynamics, that are graduated by engineering schools each year, the decreasing cost of computers, the dissemination of computer programs written originally for academic research, and more recently the advent of mini- and microcomputers. Development of programs for these machines will further accelerate the application of dynamic analyses in the design process. Also, the developers of these programs often provide guidance on their use to the engineering profession through short courses and code recommendations such as the *Tentative Provisions for the Development of Seismic Regulations for Buildings* prepared by the Applied Technology Council (ATC).

The standard mathematical model for elastic dynamic analysis of framed buildings has been well known for a number of years. It uses stiffness matrices for the columns and girders, assumes that the slabs act as rigid diaphragms in their planes, and lumps masses and mass moments of inertia at the floor levels. These building models have more recently incorporated the effect of member (or joint) size, which is important when dealing with deep columns, deep beams, and coupled shear walls. Some programs also model structural or nonstructural partitions, which will further stiffen the structure, or the deformability of panel zones in the joints, which will introduce an additional flexibility.

Though more work remains to evaluate the effect of inplane flexibility of floor slabs in shear wall buildings, dynamic analyses of typical framed structures in the elastic range can now be performed with sufficient accuracy and relative economy. The state of the art is less advanced for other types of buildings. Only a limited number of studies have been performed for buildings with flat plate floor construction, for prefabricated panel buildings, or for masonry structures; most of these studies have used finite element models, which are too expensive for routine work. Finite elements have been used extensively, on the other hand, to model components of special structures, such as nuclear power plants. They have also been used in analyses of soil-structure interaction.

Inelastic Analyses

One important requirement of dynamic analysis not met by the foregoing methods is to calculate the cumulative damage experienced by the structural members of a building subjected to strong ground shaking of long duration, such as an earthquake with a magnitude greater than 8 would generate. According to present design philosophy, most buildings should be able to undergo inelastic deformations when subjected to severe earthquake shaking. They therefore cannot be analyzed adequately as an elastic system. During recent years, equivalent linearization techniques have been developed that provide a simple way to account for one important aspect of nonlinear behavior—the changes in natural periods of vibration. In addition, various types of damping matrices have been introduced to simulate different kinds of energy dissipation that may accompany the nonlinear response. Although these procedures only approximate nonlinear behavior, they can usefully characterize the response in special situations. For example, they can be used in frequency domain analyses or probabilistic studies.

To analyze structures deterministically, true nonlinear solutions are preferred. Such inelastic dynamic analyses have three levels of complexity. Simple models, based primarily on systems with a single degree of freedom that are elastic and perfectly plastic, have received extensive use. They have led to the definition of inelastic response spectra and to the determination of rules to construct these spectra for various levels of ductility. Such studies have also led to better understanding of the key effects of inelastic behavior (elongation of the period of the system and an increase in damping) and have served as a basis for the more rational definition of the seismic design coefficient that the ATC effort proposed. The definition of ductility in terms of a displacement ratio is clear, however, only for an elastoplastic system. The relation between ductility and damage for more general systems, including the effects of deterioration, remains to be explored. Also, the relations among the ductility of a system with a single degree of freedom, the overall ductility of a structure, and the ductility required of the various members and components (which depends on the type of structure) need further clarification.

Point-hinge models with localized yielding that is confined to the ends of the members are an intermediate approach. Originally these were used mainly for research purposes, but they have seen increasing application in practice. A number of different nonlinear moment-rotation relations have been formulated to simulate the behavior of steel and reinforced concrete members. The use of an appropriate interaction diagram accounts for the effect of axial forces on the yield strength, but the coupling of axial and bending stiffness is neglected, as are the effects of biaxial bending, shear forces, and torsional moments. Analyses using this model give the ductilities at member ends, measured in terms of moments or rotations. Their relation to curvature or to damage is not always clear, particularly when dealing with significant shear forces or variable axial forces.

More complex models, which reproduce a cross section as a group of fibers, consider the spreading of yielding, the coupling between axial forces and bending moments in the inelastic range, and the effects of biaxial bending. Their use, however, is mainly restricted to academic research. Moreover, they cannot reproduce the effect of shear stresses caused either by shear forces or torsional moments, and their results are expressed in terms of quantities not directly related to damage. Two-dimensional and three-dimensional finite element models have also been used for inelastic analyses, and some progress has been made in deriving nonlinear constitutive equations for plain concrete under general states of stress. However, much work needs to be done before these models can be applied to confined reinforced concrete. Nevertheless, they can play a significant role in validating simpler models, even though they may be costly for purposes of design.

Mode Superposition Analysis

Dynamic analyses have usually been conducted in the time domain. In the last decade, however, analyses in the frequency domain have become increasingly popular, particularly when dealing with problems of soil-structure or fluid-structure interaction. In both cases the analysis entails either directly solving the equations of motion or a modal decomposition.

Determining the natural frequencies and mode shapes of a structure (i.e., solving the eigenvalue problem) has been the subject of considerable research in the last decade, particularly for systems with a large number of degrees of freedom. This research has resulted in a series of new methods (e.g., subspace iteration, quadratic reduction). Modal analyses commonly specify directly the values of damping in each mode. Approximate procedures then estimate modal damping values for systems with different types of energy dissipation in various components. A modal spectral analysis still normally combines the modal maxima using the SRSS (square root of the sum of the squares) rule, but the range of applicability and limitations of this procedure have been thoroughly investigated. Other more reliable procedures, suitable for multicomponent as well as single-component spectra, are now available that require only slightly greater computational efforts. Modal analysis is still used primarily for linear systems, but the last years have shown that modal synthesis can offer advantages for systems with well-defined localized nonlinearities, and that modal decomposition can even apply to general nonlinear systems in special circumstances.

Step-by-Step Integration

A direct solution of the equations of motion in the time domain, through step-by-step numerical integration, is the procedure most commonly used for nonlinear analysis. In the last decade the stability, convergence, and accuracy of different integration schemes have been thoroughly examined, and procedures have been proposed to derive algorithms with any desired characteristics. In most cases, however, these techniques work only for linear systems. For some time a controversy existed over the relative advantages of conditionally stable, explicit methods, which deal with lumped masses (a diagonal mass matrix) especially well, as compared with unconditionally stable, implicit methods, which can use larger time increments but require solving a system of equations at each step. Implicit methods may in addition require several iterations per step when dealing with nonlinear systems, and the convergence of these iterations may restrict the time step. A significant improvement in this respect is using a tangent stiffness matrix to represent the forces incrementally, which avoids the need for iteration.

Procedures that combine explicit and implicit methods for the same problem, the former being applied to the parts of the domain that become nonlinear, the latter to parts that remain linearly elastic and may be much stiffer, have recently been suggested. These procedures take advantage of each method's best properties. Research along these lines seems very promising, particularly for nonlinear analyses of systems with a large number of degrees of freedom.

Frequency Domain Analysis

Solutions in the frequency domain have seen extensive use in the last decade, thanks mainly to the availability of the fast Fourier transform algorithms. Researchers have investigated the relation between the discrete Fourier transform and the continuous (analytical) transform, as well as the conditions needed, in terms of frequency increment, maximum frequency, etc., for an accurate solution. One major advantage of these solutions is that they allow study of continuous field systems, including those whose properties are a function of frequency. These solutions also easily represent linear hysteretic damping using complex moduli. Their main present limitation is that they are restricted to linear systems, but important research is beginning to seek the solution of nonlinear systems in the frequency domain.

Probabilistic Analysis

The uncertainties involved in seismic analyses, starting with the definition of the design earthquake, led very early and quite naturally to probabilistic formulations. Early work centered primarily around the response of elastic systems with a single degree of freedom subjected to Gaussian white noise or simple stationary excitations. The last 10 years have seen a substantial amount of work and considerable progress both in probabilistic modeling of earthquakes, as time modulated or fully evolutionary random processes, and in applying random vibrations theory to predict the statistical response of elastic systems with multiple degrees of freedom. Recently developed rules can give the response spectra associated with a given probability of exceedance from the spectral density function of the earthquake, and vice versa. Systems with multiple degrees of freedom can be analyzed using modal analysis or covariance matrices. The probabilistic response of nonlinear systems has been studied using perturbation techniques for mildly nonlinear behavior; for more general cases, equivalent linearization procedures or Monte Carlo simulations can be applied. More work has to be done, on the other hand, to account for uncertainties in structural properties.

Multiple Support Excitation

In analyzing the dynamic response to earthquakes, analysts have customarily assumed that the same ground motions act at all points where the structure meets the ground. This assumption is reasonable for structures where the foundation occupies only a localized region, such as a high-rise building; but for structures with a great horizontal extent, such as long-span bridges, pipelines, dams, and large warehouses, the seismic waves, whose propagation produces the ground shaking, will obviously create variations in the ground motions between different support points.

Theoretical procedures for calculating the dynamic response to such varying support motions have been available for many years, but a lack of information about the actual spatial variation of an earthquake's input has made such analyses academic. Now, however, data from seismograph arrays are beginning to provide this necessary information. Consequently an important area of future research in structural dynamics is to analyze the responses to spatially varying earthquake motions and evaluate the importance of such variations on the performance of various types of structures.

Foundation-Structure Interaction

Progress to Date

In the early years of earthquake engineering, analysts of structures subjected to seismic excitations assumed that the motion at the base of the structure was essentially the same as that in the free ground surface. Both research and field evidence supported this position, mainly because design and research emphasized high-rise flexible structures. As a result, researchers concluded that the interaction of the structure with the foundation medium during an earthquake was minimal and not a subject for research.

The advent of nuclear power plants changed this attitude dramatically. Safety-related structures in nuclear power plants are usually massive and relatively rigid. The interaction between the structure and the soil affects the dynamic response of such structures during earthquakes significantly. This interaction modifies the motion of the free ground surface, and the level of this modification provides a way to define the significance of the soil-structure interaction. Dams, embedded structures, buildings with stiff shear walls, structures supported on piles, and offshore structures are other types of systems in which soil-structure interactions may be important.

Remarkable research accomplishments have been made in the area of soil-structure interaction during the last decade. Presently, the phenomenon of soil-structure interaction as it affects buildings is well understood, and the significance of the important parameters is well established, even though practitioners still differ as to which method of analysis provides better solutions. Two kinds of analysis methodologies are available:

1. The "direct" method of analysis refers to modeling a significant portion of the foundation medium together with the structure in a single system. This system is analyzed by introducing the seismic excitation at the boundaries of the soil model. Usually, finite elements are used to model this type of system.
2. The "substructure" method of analysis refers to a procedure involving three steps. First, the input motion to the structure's foundation is obtained. Second, the foundation's dynamic stiffness coefficients are calculated. Third, the structural model and the foundation stiffnesses are combined, with the complete system being subjected to the input motion obtained in the first step. Even though finite elements can be used to model the foundation in the first and second steps, a visco-elastic layered half-space continuum is commonly used to idealize typical foundations.

Computer programs for both methods of analysis have appeared during the last decade, each having its own special advanced features and limitations.

Despite this progress, a number of topics require further research. Among these are defining the ground motion, modeling the soil and structure, and improving the cost efficiency of the computer procedures.

Ground Motions

In the past the study of strong earthquake ground motion emphasized the acceleration of the free ground surface. However, where soil-structure interactions are important, several additional aspects of ground motion must be better understood:

1. The variation of ground motion from point to point at a given site, especially for large foundations, as mentioned earlier. This relates to the basic question of the angle of incidence of seismic waves.

2. The variation of ground motion with depth for analyzing embedded structures. Simplified models of the soil predict a significant reduction of motion with depth, but the reliability of these models is not known.
3. The quantitative contribution of the different types of waves in recorded ground motions. A proper analysis of soil-structure interaction requires that the types of wave and associated amplitudes of motion be identified for ground motion.

Because inhomogeneities along the travel path of seismic waves can produce variations of ground motion at a given site, the question of whether to express the input design motion deterministically or probabilistically requires further consideration. This aspect of the problem has not been studied directly, although both types of analysis have existed for many years.

Modeling of Soil

Modeling the properties of soil is of paramount importance in analyses of soil-structure interaction. Several aspects of the problem require additional research:

1. Determining the dynamic properties of soil in situ, including the effects of strain rates, and correlating laboratory test data and field information.
2. Understanding the spatial variation of soil properties, not only with depth but horizontally.
3. Modeling the variation of soil properties when subjected to different three-dimensional states of stress. Nonlinear constitutive relations or an equivalent linearization can be used for this purpose. In the latter case, the assumption of linear hysteretic damping independent of frequency needs further study.

Research needed on the direct method of analyzing foundation-structure interaction includes (1) further study of techniques for avoiding wave reflections at the boundaries of finite element models and (2) development of procedures for representing an inherently three-dimensional soil medium with a two-dimensional model. The costs of analysis increase by about two orders of magnitude if a three-dimensional model is used to represent the soil.

Modeling of Structures

Although the modeling of the superstructure is discussed elsewhere, some aspects of the structural model do influence the foundation interaction problem—for instance, different foundation elevations in a large complex. Other important considerations include the proximity of other structures, even if founded at the same elevation; the question of geometric nonlinearities due to separation of the structure and the soil, both under the foundation and along the sides of embedded structures; the treatment of foundations of arbitrary shape; and incorporation of a foundation's flexibility.

Experimental Study of Structural Properties

Background

The digital computer made possible the development of complex mathematical models that can represent a structural system and predict the effect of any given earthquake motion on that system. However, the accuracy of such predictions depends directly on the accuracy with which a model represents the structural system and with which the basic properties of that system's components are defined. The 1969 report *Earthquake Engineering Research* pointed out that experimental studies should examine the stress-strain relationships and energy absorption, as functions of strain amplitude, strain rate, and previous deformation history, of basic structural materials. The report recommended as a second step that once the above properties were established, dynamic cyclic tests on typical beam and column elements should be conducted. The objective would be to determine the strength, stiffness, ductility, and other characteristics of such typical simple elements, which would then be compared with predictions based on the material properties determined in the first step. Finally, as a third step, the report recommended dynamic and quasi-static reversed cyclic loading tests on simple beam-column subassemblages. The objective of these tests would be to determine how well predictions based on the response of simple elements could be extended to complete structures. As the ultimate proof of the validity of the laboratory and analytical work, observations and analyses were to be made of full-scale structures in earthquakes and of small-scale structures on shaking tables.

In accordance with the recommendations of the 1969 report, considerable research has been performed over the past decade on components and subassemblages subjected to simulated seismic loading. Most of that work has been on structural steel or cast-in-place reinforced concrete subjected to quasi-static reversed cyclic loadings that have stressed the components inelastically to failure. Most components have been less than full scale (one-fourth to three-fourths scale), and most investigations have been designed to develop detailing provisions for building codes governing new construction. The following sections discuss the progress and future needs of this laboratory research.

Steel Structures

Research on structural steel has generated valuable data on the strength and behavior under seismic loading of both braced and moment-resistant frames. Preferred connection details have been developed for such systems, and criteria have been established for predicting their elastic and inelastic deformations and their strength. As a result, the eccentrically braced steel frame has become a structural system that combines the desirable characteristics of both braced and moment-resistant frames.

While these studies have been valuable, they are by no means complete. Most importantly, attention has focused only on inplane deformation effects and on the characteristics of the structural components designed to resist earthquake forces. The likely performance of those components functioning within the total resisting system of the "as built" structure has not received attention. Prime factors requiring further investigation for steel structures are (1) inelastic constitutive material laws, (2) reliable procedures for predicting local or lateral torsional buckling, (3) the fatigue strength of welded connections, (4) the composite action between floor slabs and steel frames on the overall response of the structure, (5) the significance of three-dimensional mechanisms in evaluating the overall response (such considerations can arise from the three-dimensional nature of the earthquake motions, variations in the strength and stiffness of parallel frames, lack of symmetry, variations in torsional stiffness, and diaphragm action), and (6) scale effects involved in testing reduced-size components, subassemblages, and complete structures.

Reinforced Concrete Structures

Research has produced data over the past decade on the strength and ductility of reinforced concrete components, the connections between components, and both ductile moment-resistant frames and concrete shear walls. This research has shown that the coupled shear wall system and the coupled ductile frame, shear wall system are particularly well suited for moderately high to tall reinforced concrete buildings in the more intense seismic zones.

Although the study of seismic resistance in reinforced concrete components and assemblages has made significant progress, further effort must be devoted to the systematic definition of basic material properties of the concrete's constituents. Also, the mechanical characteristics of these constituents when working as a composite material should be studied. Basic data are needed on the characteristics of seismic response for (1) reinforced concrete, both confined and unconfined; (2) reinforcing and prestressing steel; (3) the bond between concrete and steel, particularly for the situations likely in practice; and (4) the transfer of shear and normal stresses across cracks. For frames, the most likely problem is not strength but the degradation of stiffness and energy capacity with cycling. The lack of sufficient information on the basic properties of the materials used in reinforced concrete frames makes the development of reliable mathematical models for quantifying those effects difficult, and the situation is even more critical for wall systems. While model tests on walls have provided considerable information, measurements of the stiffness, deformation capacity, and hysteretic energy dissipation in those tests are lacking, since the basic information on the material's behavior is insufficient. Furthermore, with reinforced concrete, as with structural steel, more attention should be given to considering the performance of "as built" structures rather than "as designed" structures, and part of this attention should focus on the contributions of nonstructural components. The influence of the slab on bending stiffness, moment capacity, and requirements for torsional compatibility needs to be determined, as does the significance of three-dimensional interactions on the overall response.

Other Structural Systems

Structural steel and cast-in-place concrete are presently the preferred materials for earthquake-resistant construction, and most current research deals with them. However, many existing buildings employ other material and have structural systems and connections that are very different from the systems and details currently being studied. High priority should be given to determining criteria for evaluating and retrofitting existing buildings. Such evaluation and retrofitting involves issues of mathematical modeling, identification of the material properties of the existing structure, determination of the likely seismic performance of the existing structure, development and evaluation of different strengthening alternatives, and determination of the likely seismic performance of the strengthened structure. Many existing buildings consist of unreinforced masonry or concrete or steel frames of inadequate strength with infill masonry panels and masonry veneers. Appropriate methods for mathematically modeling such structures need to be examined, and procedures should be identified to evaluate the trade-offs of various retrofitting schemes.

Many modern low-rise structures consist of masonry or prefabricated construction. The little research done to date on such construction has shown that realistic mathematical modeling requires careful consideration of possible rocking and sliding actions, as well as of possible local failures. Much work needs to be done to identify the basic properties of the materials used in masonry and precast concrete buildings, to understand the dynamic response measured in high-intensity reversed cyclic loading tests on typical elements and connections, and to predict the response of assemblages incorporating these forms of construction. Of special urgency is the need for information on detail design requirements to be applied in regions of relatively low seismic hazard. If all these data were available, the use of partially reinforced or reinforced masonry and precast concrete construction would probably increase in zones with all levels of seismic activity. This might make the cost of these types of construction significantly less (particularly for medium-rise housing) than the cost of construction in structural steel or reinforced concrete.

To date, little research has been done on new types of structures for seismic regions. More research of an exploratory nature on new types of structures and new approaches to seismic design would be desirable.

Laboratory Test Facilities

Research on the cyclic response properties of structural materials, elements, and assemblages, such as that mentioned in the preceding sections, has usually employed test systems incorporating electrohydraulic actuators to apply the specified loads or deformations. Many laboratories in this country have small- to medium-scale test systems of this type, but none is suitable for testing full-scale buildings. To evaluate whether full-scale testing is essential or cost effective, the United States and Japan have begun a cooperative research project to make use of a large-scale facility in Japan that can subject full-scale seven-story buildings to cyclic loading. These tests will show whether such a large-scale facility should be developed in the United States.

Shaking table studies of structural assemblages and complete systems provide the essential complement to large-scale ‘‘pseudo-static’’ testing. The significant advantage of data obtained by these tests is that they demonstrate the amount of deformation and damage to be expected from a ground motion of specified intensity; they thus indicate an earthquake’s *demand on the structure* rather than the structure’s *capacity to resist earthquakes*, which is the result of pseudo-static testing. An important feature of the U.S.-Japan cooperative project mentioned above is that the pseudo-static results obtained by testing the full-scale structure in Japan will be correlated with shaking table tests of reduced-scale models in the United States. This comparison should demonstrate the relative merits of pseudo-static and shaking table tests, indicating the validity of studies on reduced-scale models in predicting prototype behavior.

Another major advantage of shaking table tests is that they permit the observed dynamic response of a structure to be correlated with the response predicted by dynamic response analysis computer programs. Only by such direct comparison can the various assumptions incorporated into the analytical procedure be verified. Also, shaking tables provide a way to subject large-scale models to realistic earthquake shaking and can thus provide information not otherwise available. For example, two shaking tables, one at each end of a model of a long-span bridge, can enable the model's response to be studied when the two ends are shaken with different motions. The use of shaking tables for research thus complements computational research on structural vibrations and measurements of structural response during actual earthquakes. It would be desirable to expand shaking table research in the United States.

Field Measurement of Vibration Properties

Controlled Experiments

The ultimate proof of the validity of mathematical models based on laboratory experimentation and analytical procedures can only come from observations of full-scale structures. Therefore the field investigation of dynamic behavior in real structures is a fundamental part of earthquake engineering research.

Such dynamic studies can rely on either of two types of excitation:

1. Input from the natural environment, involving ambient conditions, such as wind or waves, or real earthquake ground motions.
2. Man-made input, such as that produced by vibration generators or high explosives.

With the exception of real earthquakes, all of the foregoing types of excitation are "controlled" experiments (in the sense that the general character of the input is known in advance). This section discusses briefly this kind of experiment. A discussion of research involving input from real earthquakes follows in the next section.

The most convenient sources of data on the vibrational properties of real structures are the ambient vibrations resulting from wind, microtremors, and other forces. The equipment required to record such motions is portable and easy to install. The data can be processed on line in the field, using modern microcomputer technology, so that results become available almost instantaneously. Such ambient test data provide information on the natural frequencies, mode shapes, and damping of the structure. During the past decade many tests of this type have been performed on buildings, concrete and earth dams, bridges, offshore oil platforms, and nuclear power stations, and the results have contributed to the study of soil-structure interaction and reservoir-dam interaction. Significant advances have occurred in the past decade, both in the capabilities of the experimental equipment and in techniques for using it to obtain the desired information.

The principal limitation of ambient vibration studies is that the motions being measured have very small amplitudes. Thus there are some doubts that the data represent the vibrational properties of structures during real earthquakes. For higher-intensity controlled experiments, investigators can turn to vibration generators, which introduce harmonic forces into structures by driving masses in linear or circular motion at controlled frequencies. Tests of this type typically produce dynamic responses significantly greater than ambient motions but much smaller than the damaging displacements that could result from a major earthquake. Great advances have been made in the capabilities of this type of equipment, both in the accuracy and range of the input frequency control and in the amplitude of the generated forces. Vibration generators now available can actually damage full-scale buildings. Gas jet thrusters have also been developed recently that can excite vibrations in structures on which they are mounted. The development of large-force vibration generators should be continued.

Because vibration generators can apply harmonic loads to the structure above the foundation level, they provide an excellent way to evaluate vibrational properties. On the other hand, the use of underground explosions to generate ground shaking that simulates an earthquake offers an important means for verifying techniques of earthquake response analysis.

Great advances have been made in understanding mathematical modeling through controlled vibration experiments on real structures. Such studies are needed on a much wider range of building types and structural systems in the future.

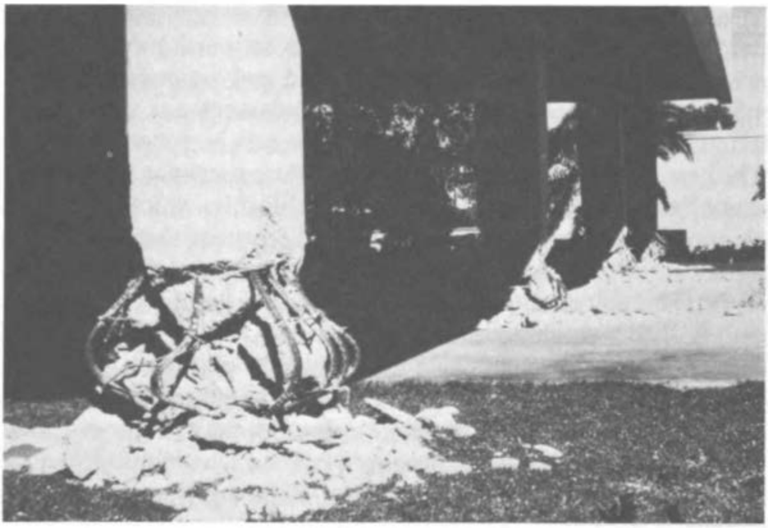
Observations from Real Earthquakes

Real earthquakes provide the most valuable data on the dynamic behavior of structures. Only in such ‘‘experiments’’ can the large-amplitude dynamic response of large structures, such as high-rise buildings, dams, bridges, nuclear reactors, and offshore platforms, be observed. During the past decade strong-motion seismographs have been installed in many buildings and other types of structures in regions of high seismicity. The records obtained from such structures now provide valuable data on real response to earthquakes. Usually, however, accelerograph records are the only measured data. An important future need is to extend the measurement system so that internal deformations and relative motions can be recorded.

The best example of a full-scale earthquake experiment is the Imperial County Services building in El Centro, California, which was provided with an extensive strong-motion recording system shortly after being completed and then suffered major damage during a severe earthquake in 1979. The selection of this test region and building was based on decision theory techniques. The structure was thoroughly studied before and after the event using both ambient vibrations and vibration generators. The damage produced by the earthquake therefore provides a great opportunity to test dynamic response analysis procedures.

Because the cost limits the number of dynamic response instruments that can be installed, the probability of having instrumentation in buildings that undergo intense earthquake motions is relatively low. Therefore it is also important to make postearthquake studies of buildings, both with and without damage, even when no input or response data are recorded. Detailed studies of buildings damaged by earthquakes reveal much about the adequacy of existing design and

The Imperial County Services building was severely damaged by the 1979 magnitude 6.4 Imperial Valley, California, earthquake. The building, designed in 1968, was located 7 miles from the fault. The motions of the building and the ground during the earthquake were recorded, giving engineers records of motions for the first time from a building undergoing severe structural damage.



The four columns at the west end of the Imperial County Services building were shattered at their bases, and the other columns were cracked from overstressing. The building has now been demolished because of the damage caused by the earthquake.

construction procedures and identify areas for further laboratory research. Similarly, dynamic analyses of buildings that are not damaged by strong earthquakes can provide important data concerning design requirements and construction practices. Inasmuch as natural earthquakes produce an important test environment at no cost to the researcher, postearthquake structural investigations are one of the most cost-effective areas of earthquake engineering research.

System Identification

As the use of experimental methods in the field of structural dynamics has increased, a need has developed for techniques to determine accurately the essential properties of a structure from tests conducted on it. System identification is the term generally used to denote this process of converting test data to system characteristics. The procedures employed usually originate in mathematical programming or optimization methods, and they usually require test data in the form of response time histories or frequency response curves.

System identification has been used to address the following subject areas:

1. Estimation of values of elastic vibration parameters from test data.
2. Determination of values of elastic structural stiffness parameters from test data showing natural frequencies and mode shapes of vibration.
3. Estimation of values of inelastic system parameters from time history test data.
4. Evaluation of strength of existing structures.

Most of the research in system identification has concentrated on estimating system parameters, although some work has been done on load identification. These studies first assume that the response equations are known and then obtain values of the parameters in these equations to produce a response that best correlates with the measured test response. The test response is typically determined in the frequency domain for elastic systems and in the time domain for inelastic systems. System identification studies have looked at buildings, bridges, and nuclear reactors, as well as many types of subjects in laboratory research.

A significant amount of work in the last decade has applied system identification techniques to inelastic structural systems. This work has gone in two directions. The first involves estimating the parameter values in a nonlinear differential equation, comparing alternate types of nonlinear differential equations, and selecting the best for correlation of predicted and measured responses. The second approach assumes that an elastic model is valid for calculating a system's response, but then identifies different parameter values in the elastic model for different time segments of the response. Research is needed on the computer programming phase of system identification, wherein programs or hardware chips are developed specifically for application to buildings, dams, and bridges.

System identification techniques have recently formed part of an overall approach to evaluating strength and to rehabilitation of existing structures. In such studies the identification procedure has included the uncertainty associated with estimated parameters from various parts of the rehabilitation. A major area of future research in system identification should consist of evaluating the existing strength of structures already built.

Research is needed on parallel full-scale and laboratory model studies to assess the accuracy of the results obtained from system identification studies. Such assessments should use measured joint rotations, relative displacements, and other higher-order response quantities.

Conclusion

Although the basic techniques of structural dynamics analysis were understood 10 years ago and had already contributed to design calculations and significant studies in earthquake engineering research, structural dynamics for earthquake engineering was really in its infancy then. Recent years have brought significant advances in the numerical procedures used to perform the analyses, and the electronic computer systems that do the work have made even more impressive progress.

With regard to the mathematical modeling of structures, 10 years ago almost no data existed on the inelastic response of structures subjected to cyclic loads. Hence realistic analyses of the damage to be expected from such loads could not be performed, nor were the data available to assess the accuracy of an analysis if one were performed. Now, as a result of extensive field and laboratory work, it is possible to formulate mathematical models that characterize real behavior as damage develops. Moreover, response data from structures subjected to real or simulated earthquake motions make it possible to verify analyses performed with these models.

The foregoing comments demonstrate that structural dynamics analysis has made very significant progress during the past 10 years. Nevertheless, future progress can be just as impressive in all aspects of the field. Continued research can lead the way toward the ultimate goal of predicting reliably how an existing structure or a new design will behave in a major earthquake.

7

Earthquake Design of Structures

The engineering design of a structure begins with the conceptual development of a building system that meets certain functional requirements. The subsequent development into a final design involves the synthesis of many items, including loadings, properties of materials, sizes of members, and the use of analysis to demonstrate the adequacy of the design.

Earthquake-resistant design is based on a knowledge of the following items: (1) the earthquake hazard at the site, (2) the response of the structure to ground shaking, (3) the stress-strain properties of the materials used in construction, (4) the performance of structural elements under earthquake-type loading, and (5) the desired safety factor or the acceptable level of damage. Once these items are known, the appropriate structural system and materials must be defined, the proper size and shape of the structural members must be determined, and the connections of the structural members must be described, all in such a way as to achieve the desired performance from the completed structure. Accomplishing this requires that extensive stress analyses and many judgmental decisions be made. In nonseismic regions, structural design seeks primarily to resist the force of gravity, which pulls steadily downward; secondarily, the design seeks to resist the horizontal pressure of the wind. In seismic regions, the design must also resist the vibratory forces generated by earthquake ground motions. This significantly increases the complexity of the design process and the knowledge and expertise required of the designer.

When seismic requirements first appeared in building codes, practically nothing was known about earthquake engineering. The 1933 Los Angeles building code, for example, merely stated that a structure should be designed to resist a steady horizontal thrust equal to 8 percent of its weight, thus treating earthquake forces in the same way as it treated wind pressures. During recent years seismic design has undergone a remarkable development, one made possible largely by the earthquake engineering research program in the United States and partly by earlier research after World War II on military protective structures. The research strongly reflected the need for new information and better methods by engineers designing such major projects as nuclear power plants, high-rise buildings, dams, offshore oil drilling platforms, rapid transit systems, liquefied natural gas (LNG) storage tanks, and oil and gas pipelines. As a result, the research and the development of seismic design went hand-in-hand.

Building codes to which ordinary buildings are designed have also experienced impressive developments, so that they are now much better suited to guide realistic design against earthquake forces. The requirements in the U.S. building codes form the basis for earthquake design in most seismic regions in the world. Clearly, the present-day methods of earthquake-resistant design in the United States represent an outstanding improvement over methods available 10 or 20 years ago.

When a building is subjected to earthquake motion, its base tends to move with the ground, and stresses and deformations occur throughout the structure. If the building is very stiff, the entire structure moves with the ground, and the dynamic forces induced in the building nearly equal those associated with the ground accelerations. If the building is flexible, differential motions of its supports and floors can induce large dynamic deformations. To survive the earthquake shaking, the building must be strong enough to resist the induced forces if it is rigid; if it is flexible, it must be able to accommodate the deformations without collapsing. In either case the building must have the capability to absorb safely the energy induced by the ground motion. The trained earthquake engineer visualizes how a building will behave during an earthquake and then designs it to have the physical properties necessary to resist or accommodate an earthquake's motion.

One of the major threats to life and property, especially in highly seismic regions, arises from existing buildings and facilities. Many structures built before good earthquake requirements were in building codes are technically deficient in the light of modern knowledge about earthquake design. The cost of rebuilding or retrofitting all such structures is probably unacceptably large, and it is most unlikely that the public would support channeling a high proportion of our resources into such a narrow program. Probably the best approach for correcting such deficiencies in areas of moderate to high seismicity is to accelerate the natural obsolescence of old buildings, promote retrofitting or strengthening of selected facilities, and adopt modern practices of earthquake-resistant design and construction for new buildings. In regions of low seismicity, the continual upgrading of engineering practice, including the enforcement of building codes, will lead to greater protection without burdensome economic penalty. In the long term a balanced program of upgrading new construction should have far-reaching benefits in providing structural resistance against earthquakes and other natural hazards. Unfortunately, in some regions in the United States it is not possible to rule out the possibility of large earthquakes in the not-so-distant future, and such an event could cause a great disaster. This is a problem that government officials are just beginning to face.

The sections that follow outline some of the developments that have led to the current state of design practice. Research during the past decade or so has played a major role in leading to advanced design methods and construction practices. The next section briefly addresses four generic structural types according to the type of material involved: (1) reinforced, prestressed, and precast concrete; (2) steel; (3) masonry; and (4) timber. Of course, many structures or facilities are of a mixed type of construction, involving different materials and construction practices. Each subsection describes briefly the state of the art of design and construction practice and recent technological developments. Because of their special importance, building code developments receive special attention. Some major research requirements are then identified. These center around such topics as field observations and measurements, experimental and analytical studies of structural resistance parameters for all types of construction materials, studies of structural response, and education of design engineers.

Later sections turn to the status of seismic design practice as it pertains to existing buildings, bridges, critical facilities, utilities, and mechanical and electrial equipment. The chapter ends with a brief discussion of the role and importance of architectural issues.

Structural Development and Materials

Reinforced, Prestressed, and Precast Concrete Structures

The research of the past 15 years has strongly affected the theory and practice of earthquake-resistant construction in reinforced concrete. Among the more important developments, the following three topics may be cited.

Changes in Design Bases

In the 1960s the theoretical understanding of how reinforced concrete structures respond to earthquakes was based primarily on concepts borrowed from World War II experimental research into the effects of blast loading on structures. However, investigations of the response to earthquake loading must take into account behavior under reversals in displacement over many seconds. This is quite different from short-duration unidirectional blast loading.

Experimental and theoretical research on energy dissipation in reinforced concrete systems has led to two significant developments:

1. The data base for technological decision, which used to recognize only the monotonic behavior of materials and structural members under blast loading, now includes behavior under cyclic loading. In this latter case the mechanism of energy dissipation is different and the possibility of low-cycle fatigue failure during nonlinear straining is important.
2. A number of active centers of experimental research staffed by a cadre of highly competent research workers have been built up in the United States. The experimental facilities at these centers should be modernized and expanded, and vigorous programs of research should be conducted.

Characteristics of Reinforcing Bars

One of the buildings that collapsed during the 1964 earthquake in Alaska was the control tower at Anchorage International Airport. A key factor leading to the destruction of the building was the improper splicing of reinforcing bars and their inadequate anchorage into the foundation. The embedment length required to anchor a bar properly for cyclic loading is a small detail, but it is critically important to the performance of reinforced concrete construction undergoing cyclic deformations. The nearby six-story Four Seasons apartment building also collapsed during this earthquake because reinforcing bars were inadequately anchored.

Immediate evaluation of available information following the earth-

This air traffic control tower at the Anchorage airport collapsed following the 1964 Alaska earthquake. Important structures in seismic regions should be designed on the basis of a dynamic analysis to ensure that they remain functional after an earthquake.

quake revealed weaknesses in most existing reinforced concrete construction and suggested that new buildings in seismic regions might require very costly designs. Eventually, information from four different areas of research resolved this problem.

1. Research on the nature of ground motion fostered confidence in prescribing the types of motions that buildings were likely to experience at their bases.
2. Experimental research provided quantitative relationships between the length of splice required to develop the strength of the bar and the degree of inelastic action.
3. Research on analytical nonlinear-response models, calibrated by earthquake simulation experiments and given input from ground motion research, defined the extent of inelastic action required at joints of reinforced concrete frames.
4. Field documentation of earthquake damage and subsequent evaluation studies helped to build confidence in these conclusions, which were based on laboratory work and analyses.

In 1981 the Building Code Committee of the American Concrete Institute proposed a revised set of practical rules for determining the length of development for reinforcing bars. In part, this was the result of these four different components of earthquake engineering research coming together.

Ratio of Transverse to Longitudinal Reinforcement

The shift of the data base for design from monotonic to cyclic loading demonstrated that transverse reinforcement cannot be considered "secondary" reinforcement in earthquake-resistant structures. Information from field studies of earthquake damage and from laboratory experiments has demonstrated the need for well-detailed transverse (tie) reinforcement to develop toughness. It is important to note that adequate transverse reinforcement, which some designers once considered an unjustified requirement or difficult to fulfill in the field, has now become everyday practice.

Steel Structures

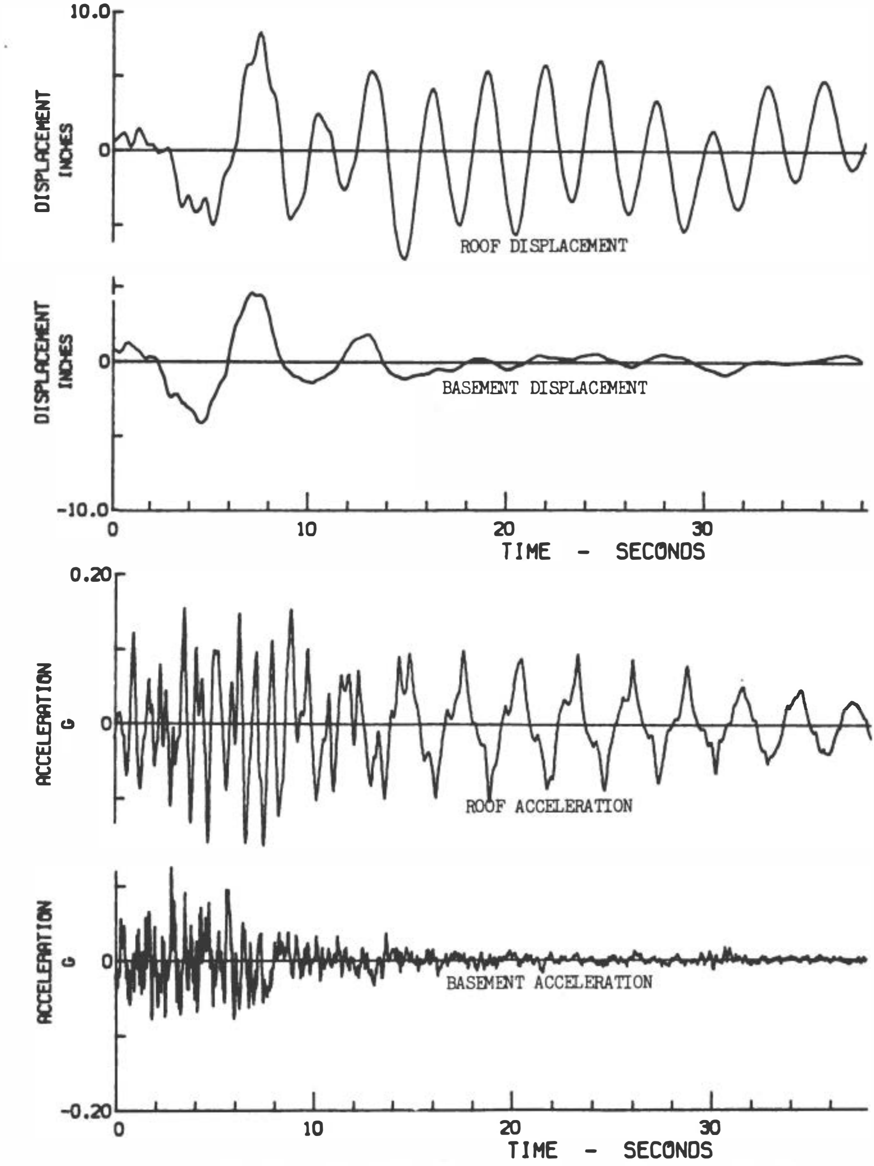
Except for those few that experienced the 1906 San Francisco and 1923 Tokyo earthquakes, few large (high-rise) steel buildings have undergone strong earthquake motions. The few large earthquakes of recent years have occurred in areas where concrete was the predominant construction material or where there were no very large buildings. The high-rise steel buildings that have experienced strong ground motions in the past decade or two include the 22-story Finance Ministry in Guatemala City (1976), the 42-story Union Bank Building in Los Angeles (1971), the 34-story Bolivar Towers in Venezuela (1967), and the 43-story Latino-Americana building in Mexico City (1957). These buildings performed well, but the ground shaking was only moderately strong.

Recent research on the earthquake resistance of structural steel buildings has emphasized the cyclic performance of members and connections when strained far into the plastic range. Although steel members have been used in buildings and bridges for many years, only a limited evaluation of their behavior during the type of motion induced by earthquakes has been undertaken. Field observations of damage from earthquakes have revealed deficiencies at the connections and at splices of members in some buildings. Tests of steel subassemblies with details similar to those in actual buildings have revealed the importance of designing to accommodate secondary effects and load misalignments that may occur during an earthquake. As a part of the recent experimental research directed at correcting these deficiencies in new designs, the method of ''eccentric braces'' has evolved as one possible way to overcome some of the deficiencies of concentrically braced frames. Several large buildings have been constructed using this principle with savings in cost.

Composite concrete-steel deck floors are employed almost universally in high-rise steel-framed building construction. In earthquake-prone areas the decks constitute an important diaphragm in the system to resist lateral forces. Based on research carried out over the past decade, a standard specification for the design and construction of metal decks was recently prepared under the auspices of the American Society of Civil Engineers.

Masonry Structures

The term masonry, as generally used in building construction, applies to an assembly of comparatively small rock, clay brick, or concrete units. Research on earthquake damage has demonstrated that the damage threshold and failure level is much lower for ungrouted and unreinforced masonry construction than for properly grouted and reinforced masonry, and this has an important bearing on life and safety. Over the years, research has been undertaken on construction techniques and engineering design of reinforced masonry, and there have been improvements in these areas applicable to both moderately and highly seismic regions. Recent earthquakes have provided information on the performance of masonry buildings, and some details of design have been modified to provide improved structures. Additional



These earthquake motions were recorded in a 17-story steel frame building. This moderately strong ground shaking produced appreciable, though nondamaging, vibrations. A 50-story building subjected to very strong shaking would deform much more.

research continues to be required on the optimum earthquake design of masonry buildings.

In the past the trade organizations of each masonry group conducted most of the research on masonry structures. Early research sought to determine nonseismic properties. In recent years considerable testing on masonry systems has used static loading or slowly reversing loading. These test data have been used to define the limits for simplified design procedures and to upgrade code provisions and construction practice. In spite of these advances, however, the designer currently has little information available on the actual strength-deformation characteristics of masonry systems when subjected to earthquake loadings.

Wood Structures

The field investigations of wood buildings following the 1971 San Fernando earthquake and other less severe earthquakes in California have confirmed the historical record of wood structures—that they generally perform well during earthquakes. When a structure performs as a unit, it suffers relatively little damage; however, connections, anchorage details, and bracing must be carefully designed and constructed.

Wood residences and small commercial or industrial buildings possess qualities that enable them generally to survive strong shaking. Wood has high stiffness-to-weight and strength-to-weight ratios, it behaves as a linearly elastic material, and it exhibits a time-dependent strength that for short durations is several times greater than the standard allowable design stresses. The number of partitions, the encasing finish materials in the floor, roof, and wall assemblies, and the large number of fasteners permit a redistribution of forces and deformation. Fortunately, for wood structures the failure of a single connection or element normally does not lead to collapse or even to severe damage.

In the 1906 San Francisco earthquake and in the 1933 Long Beach earthquake, wood buildings did suffer considerable damage because of weaknesses introduced by construction practices. Over the years, as earthquake damage disclosed weaknesses, construction practices were improved, so that in general these nonengineered structures now perform well during earthquakes. However, new earthquakes frequently disclose new weaknesses, so there is still room for improvement.

Building Codes and Standards

Building codes are primarily technical legal requirements that are based on existing standards for the design, manufacture, installation, and use of building materials and components. Building codes in the United States are drafted by several different agencies and are officially adopted by city and county governments. Over 400 organizations in the United States develop building standards, including trade associations, professional societies, testing laboratories, federal and state agencies, and manufacturers.

The first model earthquake code prepared by building officials was developed in 1927, though it was never put into effect by a city (see Table 5). Today there are essentially three principal model codes that govern seismic structural design, the Uniform Building Code, the Standard Building Code, and the Basic Building Code. For the most part, the seismic design requirements in the model codes were patterned after recommendations developed by the Structural Engineers Association of California (SEAOC). The SEAOC recommendations were developed voluntarily by concerned professionals. The American National Standards Institute and the American Concrete Institute have standards or provisions that address seismic design; in a similar vein many trade groups and government agencies have standards or guides addressing various aspects of seismic design. For example, there are earthquake design codes and standards for highway bridges, petroleum storage tanks, high-rise elevators, electrical equipment, and other structures.

Adoption and enforcement of seismic design requirements at the state and local levels vary widely throughout the United States. A 1977 survey by the National Conference of States on Building Codes and Standards indicated that about one quarter of the states had statewide building codes.

Another important aspect of the building design process is the supervision of construction, which can have an important influence on seismic resistance. Differences between the ''blueprint stage'' and the ''as built'' structure can have a very important effect on the susceptibility to damage. Postearthquake investigations often reveal substandard construction practices that supervision during construction would

TABLE 5 Seismic Design Codes and Provisions in the United States

Date	Code or Provision
Post-1906	San Francisco rebuilt to 30 psf wind
1927	First seismic design appendix in Uniform Building Code ($C = 0.075$ to 0.10)
1933	Los Angeles City Code ($C = 0.08$), first enforced seismic code
1943	Los Angeles City Code ($C = 60/(N + 4.5)$, N greater than 13 stories)
1952	ASCE-SEAONC ($C = K_1/T$, $K_1 = 0.015$–0.025)
1959	SEAOC $V = KCW$, $C = 0.05/(T)^{1/3}$
1974	SEAOC $V = ZIKCSW$
1976	UBC $V = ZIKCSW$
1977	ATC-3 Tentative Recommendations

NOTE: W = weight of building, V = base shear, T = period of vibration, N = number of stories, and C, K, Z, I, S = numerical coefficients.

have eliminated. Informal observation also suggests that enforcement of building codes may be lax except in the western states.

The State of California has adopted a number of earthquake design requirements, which add to local building codes. Following the 1933 Long Beach earthquake, the Riley Act established a minimum level of earthquake resistance for all buildings except farm buildings and some dwellings. The Field Act of 1933 required earthquake-resistant design of public school buildings, and the Hospital Act of 1972 specified provisions for the seismic design of hospitals that would ensure their ability to function after an earthquake.

In recent years there has been increasing research on design concepts based on probabilistic approaches. This activity has resulted in a reexamination of past data, a close analysis of design concepts, and a formulation of design provisions to make them more logical for practitioners. Much remains to be done to apply such research to assessments of seismic risk, particularly in areas of low seismic risk, and to adapt such research to practical design and construction practices.

The National Science Foundation and the National Bureau of Standards, with participation by design professionals, researchers, state and local government representatives, and representatives for model codes and federal agencies, recently sponsored the drafting of design provisions that reflect the latest thinking in earthquake engineering. These provisions, developed under the guidance of the Applied Technology Council and incorporating modern seismic design philosophy and approaches, are currently being evaluated under the auspices of the Building Seismic Safety Council for possible use throughout the United States. This advance in earthquake engineering, which is of potentially great value to society, came about only because of the major federal emphasis on earthquake hazard mitigation and associated research.

Research Requirements

1. Field Observations and Building Instrumentation

In the last decade the understanding of earthquake ground motions has significantly expanded as a result of the accelerograms provided by the enlarged program of strong-motion instrumentation. It is important that this data acquisition program be continued in an expanded form, but several different types of additional instrumentation are also needed: (a) instrument arrays for making measurements at the surface and at depth to provide a more detailed understanding of the ground's influence on seismic waves and of the ground-structure interaction and (b) instrumentation in buildings to record their motions and deformations during earthquakes. The detailed understanding of the damage mechanisms in buildings that result from earthquake shaking is presently very limited. Even though many buildings in the western United States have been severely damaged by ground shaking, knowledge thus far is limited essentially to the recordings made in the Imperial County Services building during the 1979 Imperial Valley earthquake. Buildings damaged during earthquakes could provide the raw data for research on damage and failure mechanisms, but in the past not enough in-depth research has been done in this area. It is important that more such research be done following future earthquakes on damaged as well as undamaged buildings.

2. Laboratory Research Facilities and Experimental Research

Structural research laboratories at universities in the United States, which provide basic data needed for the development of earthquake engineering design, do not have the modern laboratory equipment that they should possess. The earthquake engineering research laboratories in Japan, for instance, are in many ways better outfitted for experimental research than are the laboratories in the United States.

Experimental laboratory research in the United States should build up the body of information needed to advance seismic design. A wide range of studies, using both models and full-scale elements and structures, should be undertaken on the static and dynamic loading of components and building systems. For every kind of construction material there is a need for research, analytical as well as experimental, on the nonlinear behavior of structural elements and assemblies and on methods of maintaining strength and ductility during large deformations. There is a particular need for more information on the properties of structural joints and connections that are subjected to cyclic stress and strain beyond their yield points.

3. Stress Analysis Research

A basic part of design is the computation of stresses and strains in structural members, in beam-column joints, and in connections between members. In earthquake engineering, dynamic analyses provide information on the forces, bending moments, and torsional moments in the structural frame. From these the designer must compute the stresses in the members, joints, and connections and make the design accordingly. There is room for improvement in presently used methods of both dynamic analysis and stress analysis for steel, concrete, and masonry structures. There is a special need for simplified methods of analysis that enable designers to understand the physical bases of a situation and yet do not require overly elaborate computations.

Existing Buildings

Examinations of buildings damaged by earthquake motions have revealed that deficiencies in design or construction have often lowered their earthquake resistance. Buildings designed under building codes without earthquake requirements are usually very susceptible to seismic damage, and even buildings designed under seismic code requirements can have such deficiencies. It is not desirable to wait for an earthquake to reveal these deficiencies. Rather, the resistance of buildings in a city should be assessed before the earthquake, so that appropriate action can be taken.

The magnitude of the hazardous buildings problem is enormous. Fortunately, large earthquakes are infrequent occurrences, but that they will eventually occur is inevitable. The number of buildings of questionable adequacy in metropolitan Los Angeles alone is estimated to be in excess of 12,000. Currently the City of Los Angeles has passed an ordinance that will reduce the hazard by requiring selective strengthening of hazardous buildings. The cost of reinforcing these substandard buildings is estimated to be in the billions of dollars.

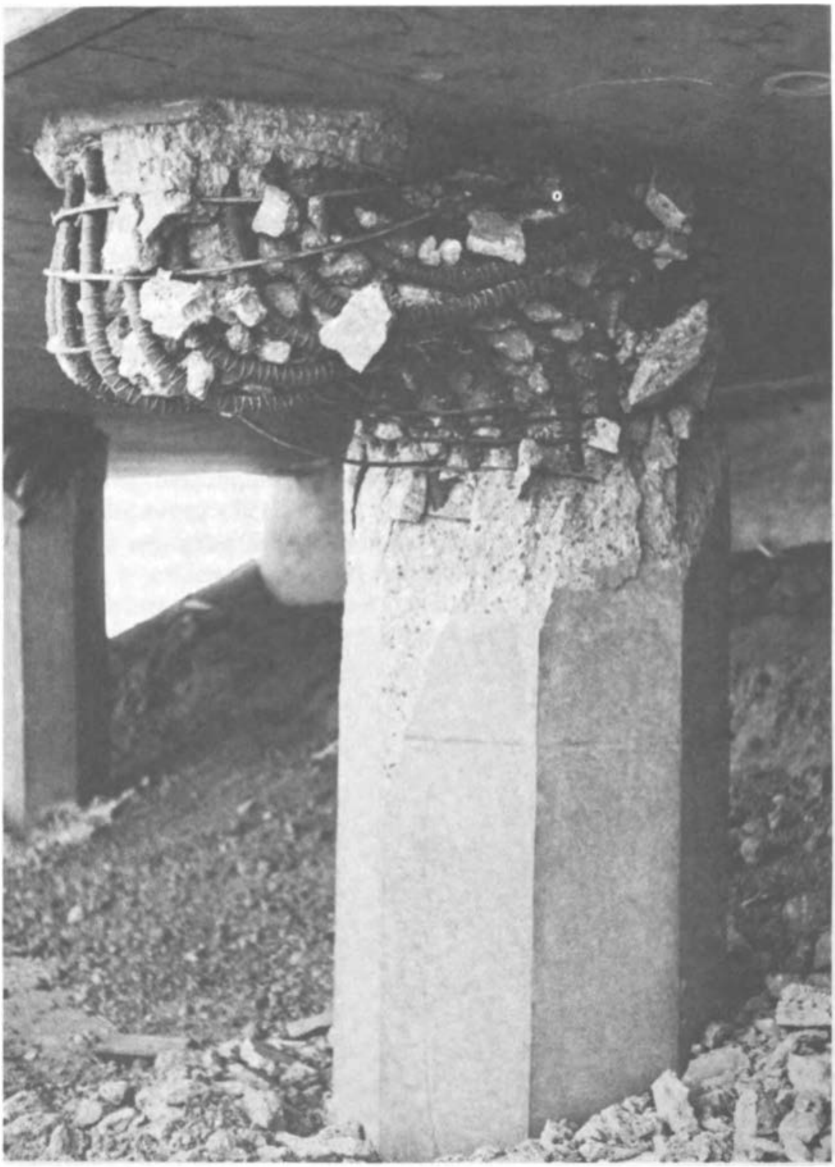
The situation is truly staggering when considered on a national scale. Damaging earthquakes have occurred in 37 states, yet in reality few communities outside the western United States have even modest earthquake design requirements in their building codes. An all-out program of building reinforcement (as well as equipment upgrading) would take decades to accomplish and, when completed, might prolong the use of otherwise obsolete buildings in an effort to obtain some return for the enormous resources spent in reinforcing them. This illustrates that in addition to engineering and economic barriers there are important governmental and social questions. At present, the existence of the problem is recognized, but no one knows how to solve it. As a beginning there is a need for selective research on the identification and assessment of hazardous existing buildings, followed by development of effective means of strengthening such buildings.

The federal government should take the lead in reducing the earthquake hazards posed by existing inadequate facilities. The Department of Defense and the General Services Administration are responsible for maintaining over 400,000 federal buildings. Following the 1971 San Fernando earthquake, several agencies initiated programs to evaluate the potential hazard of their facilities and to take corrective action. The Disaster Relief Act of 1974 requires federal agencies, when authorized by the President, to carry out such activities in accordance with standards prescribed by the President. The Veterans Administration, the U.S. Army Corps of Engineers, the Naval Facilities Engineering Command, and the General Services Administration have initiated such evaluations, but progress has generally been slow because of a lack of funds, low assigned priority, and other factors.

Bridges

The 1971 San Fernando earthquake was a major turning point in the development of seismic design criteria for bridges in the United States. Prior to 1971 the specifications of the American Association of State Highway and Transportation Officials (AASHTO) for the seismic design of bridges were based on early building code requirements. In 1973 the California Department of Transportation introduced new seismic design criteria for bridges, which included consideration of the proximity of the site to active faults, the response of the soils at the site, and the dynamic response characteristics of the bridge structure. In 1975 AASHTO adopted interim specifications applicable generally to all regions of the United States based on the 1973 provisions of the California Department of Transportation. These advances in bridge

This freeway interchange bridge in Sylmar, California, collapsed during the 1971 San Fernando earthquake. In the lower right-hand corner a collapsed overpass bridge has been partly cleared away. In the center of the photograph can be seen a large new juvenile detention facility, which was so badly damaged that it was later demolished.



These columns supporting a reinforced concrete highway bridge were damaged during the San Fernando earthquake. In the region of strong shaking, 42 freeway bridges were significantly damaged and 5 collapsed. Since the earthquake, research has been carried out on the earthquake vibrations of bridges, and the design criteria have been completely revised so that the strength of a new bridge is more commensurate with the shaking to which it might be subjected. Existing bridges have also undergone retrofitting to prevent failures such as that shown here.

design were made possible by the availability of information that earthquake engineering research had developed.

The unsatisfactory performance of bridges in the 1971 San Fernando earthquake and the 1964 Alaska earthquake stimulated new research on the seismic behavior of bridges, and in 1981 a design guide for medium-length bridges was issued under the auspices of the Federal Highway Administration and the Applied Technology Council. Highway departments are now evaluating these provisions on a trial basis before they are incorporated into future AASHTO specifications.

Because funds are not available to replace many existing bridges, cost-effective techniques for upgrading the seismic resistance of bridges should be developed and implemented in seismic regions.

Much research remains to be done on the seismic design of bridges, especially as it relates to foundation design, techniques for accommodating the movements of abutments, and the development of design procedures and criteria for long-span bridges.

Critical Facilities

Avoiding earthquake damage to critical structures and facilities—that is, installations whose failure could seriously affect the public through loss of life, injury, large financial loss, social impact, or degradation of the environment—has a high priority. Such facilities include nuclear power plants, sites for nuclear fuel reprocessing and for storage and isolation of high-level radioactive wastes, special chemical processing facilities, liquefied natural gas terminals, offshore petroleum facilities, major pipelines, large dams, and certain types of utility lifelines. Facilities that are required to remain in service following an earthquake to care for the safety or health of the public are also often considered critical facilities. Such facilities include hospitals, public safety agencies, such as fire and police units, and life support systems, such as water and fuel lines or tanks and some highways.

The earthquake-resistant design of critically important facilities normally entails a much more extensive effort, in terms of siting, development of design criteria, the actual design, and construction, than goes into the design and construction of a typical building under standard building codes. The last decade has seen major advances in the state of the art for design of such facilities. The advances were based largely on the increased knowledge and understanding of strong ground motions and structural response and on the greatly enhanced ability to analyze the dynamics of major structures and associated systems. The records from the 1971 San Fernando earthquake and the 1979 Imperial Valley earthquake have more than doubled the total data base for ground shaking. Analyses of these records have increased the understanding of the strength, nature, and variability of earthquake shaking and of the responses of structures to ground motion. The rapid development of digital computers and of computational techniques in structural dynamics have greatly extended the capabilities of earthquake design procedures.

By way of example, the development and application of the finite element method to the earthquake response of dams has been a major advance in earthquake engineering practice. This development has made it possible to estimate the effects of earthquake shaking on a large critical facility. It has also enabled earthquake engineers to go back and examine in some depth some older dams that may pose a hazard to public safety. Another major example concerns the development of approaches for designing and evaluating nuclear power facilities and their containment and safety systems. Also, the trans-Alaska pipeline, stretching some 800 miles across Alaska, was designed with modern earthquake engineering techniques, as was the Gas Centrifuge Enrichment Plant near Portsmouth, Ohio. At present the Technical Council on Lifeline Earthquake Engineering of the American Society of Civil Engineers is developing a document entitled *Seismic Design Guidelines for Gas and Liquid Fuel Lifelines*. Other studies by the same council are under way in the areas of electrical utility substations and water and sewerage facilities.

In spite of this increased ability to make seismic designs, there remain uncertainties that require further research. One of these arises from the lack of data on ground shaking very close to the causative fault. The inability to speak precisely about this near-field ground motion often leads to public concern. There is also a need for further research on the seismic design of complex equipment installed in critical structures, such as piping systems, mechanical and electrical control systems, and so on. Among the more important topics needing additional research are (1) improved understanding of strong ground shaking and its spatial variation, (2) appropriate levels of acceptable risk associated with critical facilities, and (3) the development of consistent structural design criteria.

Military Protective Structures Applications

The military protective structures program received great emphasis during World War II and continued thereafter for a decade. This intensive program of research funded by the Department of Defense provided a base of fundamental information on materials, structural response, and structural behavior and led to the initial development

The Department of Energy (DOE) is constructing the nation's first Gas Centrifuge Enrichment Plant (GCEP) in the eastern United States near Portsmouth, Ohio—a venture that will commercialize the high technology of the gas centrifuge enrichment process. During the GCEP's design, the DOE recognized the need for seismic criteria to provide adequate safety, protect their capital investment, and ensure continued operation in the event of an earthquake. As a result, the GCEP became one of the first nonreactor facilities in the eastern United States to be designed according to seismic requirements beyond those specified in current building codes. Engineering research was extremely beneficial in developing the seismic criteria, criteria that went beyond the requirements of the building code but did not require the stringent construction specified for nuclear plants. In addition, engineering research allowed "long-period motion" to be considered for the GCEP components sensitive to such motion. Long-period motion would be experienced at the plant if the 1811-1812 earthquakes near New Madrid, Missouri (approximately 400 miles away from GCEP), were to recur.

of modern techniques of dynamic analysis. For many years, extending even to the present, this military-based reservoir of information proved to be a valuable resource throughout the general applied area of structural dynamics dealing with earthquake engineering, explosions, and other situations of transient loading.

The next major research effort in the area of structural dynamics occurred with the buildup of the earthquake engineering research program. Many of the recent research developments arising from the earthquake engineering program have found application in military programs, especially in the area of analysis. This important interrelationship and technical transfer will continue to be of great national importance.

Utility Lifelines

It has been over 10 years since the 1971 San Fernando earthquake awakened the engineering community to the vulnerability of utility lifelines to strong earthquakes. For the most part, seismic considerations played little part in the original design of such facilities as underground water and sewer lines, gas pipelines, electrical substation equipment, and communications systems. All of these have suffered damage in recent earthquakes.

Ground motion criteria applicable to conventional structures with relatively small foundation dimensions are not suitable for long lifeline structures. The variation in ground motion from point to point along such structures must be considered in seismic design. Often, such structures are sensitive to strain or elongation before failure is reached. Thus ductility in the materials used and flexibility in the joints become critically important factors in the seismic design of lifelines. Likewise, details such as tying down or bracing equipment and allowing adequate slack in electrical connections are critical.

At the same time, progress has been made in understanding the effect of an individual component's failure on the servicability of entire systems. Lifeline networks are often highly redundant. Thus the failure of a component may not appreciably affect more than its local neighborhood. Though still a relative young field, seismic risk analysis of network systems has furthered our understanding of such relationships. Such studies also permit the incorporation of economic principles.

Despite the strides made in the last several years, the state of the art in earthquake engineering for lifelines is still far behind that of earthquake design for conventional structures. One need is to make the utilities and design communities aware of the problems and their possible solutions. There is a great and urgent need to expand the experimental data base for lifeline systems.

Mechanical and Electrical Equipment

The first concern of the earthquake engineer is to protect human life. Following the 1971 San Fernando earthquake, earthquake engineers also recognized the need to design lifeline systems to resist earthquakes so that vital public services could be maintained. These systems had been largely neglected prior to this earthquake, which revealed a number of weaknesses in design.

In our modern technologically based society, much of our physical and economic well-being is directly tied to the proper functioning of various types of machines or equipment. This is true across a broad spectrum of categories, including health care equipment, equipment related to emergencies and national security, data processing equipment, communications equipment, and industrial machines and equipment. As specific examples, one could cite hospital life support equipment, police, fire, and military rescue equipment, computers, electronic switch gear, pumps, generators, storage and warehouse equipment, and the whole range of manufacturing equipment, from that used to produce small electronic chips to that used to produce aircraft parts. In many high-technology industries, the capital investment in equipment may equal or exceed the investment in structures. Much of this equipment is often extremely difficult to replace. A large earthquake in a region such as that where the highly concentrated semiconductor industry in California is located would have a major national economic impact.

Despite the enormous exposure that equipment have to be damaged by earthquakes and the clear benefit to be derived from better design, relatively little has been done in this area. The main reason for this lack of activity may be that the United States has not yet experienced the damage that would result from a large earthquake near a major industrial center. It is regretful if such a stimulus is required to face this problem.

In some respects, the response of equipment to an earthquake resembles that of structures, but there are significant differences. Equipment may have elements that are necessarily quite fragile, certain items of equipment may require isolation from surrounding structures, equipment supports are often highly nonlinear even for small motion, and equipment may be subjected to levels of excitation that are highly amplified by a surrounding structure. All of these factors make analyzing and designing equipment for seismic loading difficult, but application of modern principles of seismic design can overcome these difficulties. One potential advantage of equipment systems over structures is that they can be more easily controlled during adverse conditions. This observation has led to proposals, which especially apply to some industries, for the installation of subscription-supported early warning systems in high-exposure areas. Such systems would provide several seconds of warning in the event of a major earthquake so that equipment could be configured for survival.

It is important that significant steps be taken in the design and retrofitting of equipment before a major earthquake occurs in an area of high exposure. A plan for dealing with the seismic design of equipment would include (1) development of analysis techniques to study highly nonlinear equipment systems, (2) assessment of existing information about equipment resistance (arising primarily from military and nuclear power applications) and full-scale testing and instrumentation of prototypical equipment items, (3) development of simple techniques for specifying floor-level seismic inputs for nonstructural and equipment systems, (4) upgrading of sections of existing codes and standards related to equipment or the creation of special criteria to reflect current research findings on the earthquake response of equipment, and (5) consideration of the use of active control systems to minimize earthquake damage to selected equipment. One of the more pressing research needs in the next decade is to assimilate the available information and theories pertaining to the behavior of equipment during seismic excitation, with the goal of preparing design guides for use in practice.

Architectural Issues

The study of structures that are damaged by earthquakes has shown that architectural decisions based on considerations of appearance, function, and other such concerns can greatly influence the seismic resistance of buildings. These decisions affect the locations of columns and beams, determine whether or not there are force-resisting walls and where such walls are located, and influence other matters of engineering importance. For example, the six-story Olive View Hospital building in Sylmar, California, was essentially a concrete box, but for functional reasons the first story had no walls, only slender columns. The result was a massive five-story concrete box supported on relatively flexible columns, and during the very strong shaking of the 1971 San Fernando earthquake the first-story columns were so badly damaged that the structure was later demolished.

Unfortunately, seismic design is only one of many issues that call for the attention of the architect. Consequently, the architect relies on the structural engineer to satisfy the code authorities while giving him the freedom to express his creativity with as little constraint as possible. A similar situation has largely prevailed in the area of research; architectural researchers have, until recently, left earthquake research to engineers and geologists. However, in the last decade some architectural researchers have begun to work in this area. The result has been the emergence of a unique body of work, characterized by the typically integrative viewpoint of the architect.

By 1975 it had become clear that the role of the architectural researcher in this field needed definition. Accordingly, the American Institute of Architects' Research Corporation, funded by the National Science Foundation, organized a workshop on earthquake hazard mitigation for the architectural profession and developed an agenda for architectural research in this field. In 1976 the National Science Foundation awarded the first major research grant for an architectural topic, on the subject of building enclosure and finish systems. In the next year the AIA Research Corporation organized the first of three very successful summer sessions for architectural faculty of universities, with an object of helping to introduce seismic design into architectural curricula.

At present the need and potential for architectural research on seismic issues can be summed up in four types of research that are necessary, feasible, and are currently very neglected. These are (1) research on the physical performance of a building that emphasizes the architectural configuration as a major determinant of performance; (2) research on the particular seismic hazards, to life and property, presented by different building types; (3) research on the behavior of occupants in relation to the architectural setting; and (4) research on the nonstructural components of a building and the ways in which they influence the seismic hazard. These topics are discussed in more detail below.

Building Configuration and Seismic Performance

The architectural configuration should be studied because design and construction for earthquake resistance start with the general concept of the building. As the architect conceives the size and shape of the building—low or tall, broad or narrow—his work influences or even determines the kind of resisting systems that the engineer can use. It may even determine the extent to which those systems will, in the broadest sense, be effective.

Researchers have found that many failures of engineering detail that result in severe damage or collapse often originate as defects in the concept or configuration of the building. In other words, the configuration of a building can be such that, either as a whole or in some part, the resulting seismic forces place intolerable stress on some specific element or connection.

Seismic design, then, is a responsibility shared by the architect and the engineer. If the architect gives the engineer a building concept that is fundamentally poor in earthquake resistance, the engineer's task in ensuring a safe building will be more difficult, more expensive, and possibly even impossible. Research in this area has concentrated on identifying the problem and analyzing it in conceptual terms. Detailed analyses are now under way on configurations that have been identified as problems, such as houses over garages and split-level houses, which were found to be vulnerable in the San Fernando earthquake. Further research, in the form of analysis and model experiments, is needed on identified problem shapes in large buildings.

Seismic Hazard and Building Type

Research on hazards by building type involves the interaction of the building's performance and the performance of humans in the earthquake environment. Again, the architectural orientation is of unique value here, drawing together an understanding of engineering, the building's operation and organization, human behavior, and the economic context.

One such study looked at fire and police stations as a type of building, choosing these buildings because of their critical functions in an emergency. This is a good example of a building type in which the conventional criteria of the seismic code and purely structural approaches may prevent loss of life through collapse but do nothing to prevent loss of function through, say, a small distortion in the frame that surrounds the access doors for equipment. Other studies are under way on hospitals and office buildings in the earthquake environment.

Behavior of Occupants in Earthquakes

Research on the behavior of occupants is important because detailed information on how people behave in an earthquake is needed to devise appropriate educational and managerial approaches to hazard mitigation. Only by knowing how people behave in typical social and physical settings—alone or in groups, in offices, homes, or hospital rooms—can appropriate safety measures be devised. Researchers took the opportunity presented by the near collapse of the Imperial County Services building in the 1979 Imperial County earthquake to build a detailed picture of what people do in an earthquake. Essentially, they asked two questions of the approximately 100 people in the building: Where exactly were you at the time of the quake, and what precisely did you do? Of the 100 people, 30 were well enough trained to follow the standard recommendation to get under their desks. Of these, 15 had their desks move away from over them, and one was hurt in the process. This says that more information is needed about the behavior of components and that recommendations for action should perhaps become more specific, both for the building and for the setting. The standard recommendation to get under a doorway may make sense in an old single-family house; it makes no sense in an office building with lightweight partitions and doors with glass over the transoms.

Nonstructural Architectural Components

Architectural components are those elements—exterior walls, windows, partitions, ceilings, finishes—that transform a structure into a building. They provide the building with its environment, surrounding occupants at work or at play, at their homes, offices, or institutions. The idea that these nonstructural elements play a very important role in the seismic performance of buildings began to become apparent in the 1964 Alaska earthquake, and even more so in the 1971 San Fernando earthquake. Experience in the 1972 Managua, Nicaragua, earthquake highlighted the extreme differences that the structural design of a building can make in damage to nonstructural components. Two adjoining multistory office buildings suffered comparable, relatively light structural damage, well below collapse or life-threatening levels. But the Banco de America, a stiff shear wall structure, suffered modest nonstructural damage, whereas the Banco Central, with a moment-resisting frame, underwent large deformations that caused extensive interior nonstructural damage, as well as modest damage to the primary structure. This contrasting behavior clearly showed that structural performance and nonstructural performance were interrelated.

Nonstructural components have a fourfold influence. First, their presence may modify the structural behavior of the building in detrimental ways, that is, the building structure may not behave the way the engineer conceived in his design. As a consequence, the stresses in the structure may be increased in one part and decreased in another.

Second, damage to nonstructural components may make the building nonfunctional or useless, even though the building's structure performs adequately. For example, past earthquakes have put hospitals out of operation even though their structural elements were not damaged. Essential buildings tend to depend on nonstructural equipment and services for their continued function. At present a hospital, police station, or fire station can perform perfectly in an earthquake within the structural intent of the code, but be totally useless for hours, weeks, or months because of damage to its utility services and equipment. This may entail not only loss of essential services but also severe economic loss.

Third, damage to nonstructural components may cause death and injury through falling light fixtures, collapse of filler walls, toppling file cabinets, the blocking of escape routes, and fire. At present these hazards are recognized, but little detailed information exists to estimate the real danger. Press reports tend to stress the human aspects of this problem by focusing on extreme cases—the single person killed by a light fixture, or the single person rescued from under a desk after several days in a collapsed building.

Finally, the direct economic loss in nonstructural components, combined with indirect losses of revenue caused by lack of function, may create serious problems for the owner—and for society—even though no lives are lost or injuries incurred. Besides the replacement

These library shelves collapsed during earthquake shaking. Equipment, bookshelves, lighting fixtures, and all other items that could be hazardous must be designed to withstand earthquake forces.

cost, indirect economic losses result from loss of revenues in commercial and industrial facilities. In marginal enterprises such losses can bankrupt a business and severely disrupt the lives of owners and employees.

City Planning

Many decisions made by architects, city planners, building officials, and others have long-term effects on the ability of a city to resist earthquake ground shaking, to cope with a earthquake, and to recover from an earthquake disaster. This is a field in which little research has been done despite the evidence provided by past earthquakes about the consequences of wrong planning decisions. There is a great need for research and educational efforts in the area of city planning for earthquakes.

Conclusions

As this chapter briefly documents, significant advances in earthquake engineering have clearly been made. Observations following earthquakes have shown that well-designed and constructed buildings perform quite well. Earthquake engineering research sponsored by the National Science Foundation and undertaken in the last decade has already significantly influenced the design of major buildings. It has led to new building code provisions that are nearing application, to current preparation of guidelines for the design of major gas and oil pipelines, and to essentially immediate application in the development of design criteria, design procedures, and review criteria for all types of critical facilities (nuclear power plants, offshore platforms, large dams, major gas and oil pipelines, LNG facilities, etc.)

Close review of the structural and architectural areas within the earthquake field suggest that the following seven areas, among the many important topics for future research, deserve significant support.

1. Development and installation of instrumentation in structures and facilities generally, as well as in the near field, to acquire data that can be used to improve structural performance and design procedures.
2. Experimental laboratory research to acquire more information on the physical properties of structural elements, structural assemblages, and electrical and mechanical equipment under static and dynamic conditions. Such studies must be closely correlated with appropriate analytical efforts and with basic studies of behavior that consider excitation, response, and damage assessment. Associated with this topic is the matter of upgrading laboratory equipment, which is clearly a neglected area.
3. Development of reliable and easily applied methods of analysis and design that can be employed by the practicing engineer.
4. Identification and assessment of hazardous existing buildings, and the development of techniques for repairing and retrofitting them.
5. Development of many types of application data (codes, standards, guidelines, special criteria, etc.), incorporating the latest research results, for all types of structures, critical facilities, and especially mechanical and electrical equipment.
6. Additional attention to architectural considerations, including building configurations, building types, occupant behavior, and nonstructural components.
7. Increased study of planning issues related to the earthquake problem, including land use planning and aspects of long-term recovery and reconstruction.

8

Seismic Interaction of Structures and Fluids

Many important structures in seismic regions interact with fluids during earthquakes, and this interaction affects the seismic forces acting on the structure. Such structures include dams, bridge piers, harbor walls, petroleum storage tanks, water storage tanks, offshore drilling platforms, and submerged structures.

When a structure in contact with a liquid is subjected to a ground shaking, the fluid pressures exerted on the structure change in intensity and distribution from those corresponding to a state of static equilibrium. The resulting increments of fluid pressure create time-dependent hydrodynamic forces that may significantly affect the response of the structure. The motion of the structure also induces waves in the liquid, which carry energy away from the structure and further modify its response. Evaluating these forces requires consideration of the motions of the liquid, of the structure and its foundation, and of the interaction or coupling among the motions of the component systems.

This chapter examines the seismic response and design of three classes of structures that impound, contain, or are surrounded by liquid. The systems discussed include dams, liquid storage tanks, and offshore platforms. Only concrete dams are considered, since Chapter 5 considers the seismic design of earth dams.

In the preceding examples the earthquake-generated motions of a structure are imparted to the fluid with which it is in contact, but the reverse can also happen. The earthquake can generate wave motions in bodies of water that then exert forces on structures. For example, earthquakes generate tsunamis that can heavily damage coastal structures, as happened in the 1964 Alaska earthquake, which badly damaged the towns of Valdez, Seward, and Kodiak. In addition, earthquakes can generate damaging waves, called seiches, in inland bodies of water such as lakes and reservoirs behind dams, as happened during the 1959 Hebgen Lake earthquake in Montana. Although only a small fraction of earthquakes generate tsunamis or seiches, these waves have the potential for great destruction, and the hazard they pose should not be overlooked when considering the earthquake problem. The latter portion of this chapter discusses the tsunami problem.

This water tank collapsed in the magnitude 6.4 Imperial Valley, California, earthquake of 1979. The function of such tanks is to provide high water pressure in distribution pipes. If such tanks are part of the fire-fighting system, their collapse may have serious consequences.

The treatment of each topic begins with a description of the problem and its importance. Recent major research accomplishments are then reviewed, along with their benefits to engineering practice. Finally, current research needs and challenges are identified.

Concrete Dams

Description and Importance of Problem

There are many thousands of dams in the United States. Over 1,000 are in California alone, and many more are in other regions of the country where the possibility of earthquake shaking must be accepted. The consequences of a large dam failing can be disastrous, so the seismic design of dams is an important part of earthquake engineering. Fortunately, a large earthquake has not occurred to date close to a major concrete dam in the United States with a full reservoir. However, earthquakes with magnitudes of approximately 6.5 did occur close to Koyna Dam in India in 1967 and Hsinfengkiang Dam in China in 1962. Koyna was a large concrete gravity dam, and Hsinfengkiang was a strengthened concrete buttress dam. Both were overstressed by the earthquake motions and both were damaged to an alarming degree.

The Pacoima concrete arch dam was strongly shaken during the San Fernando, California, earthquake at a time when its reservoir was only partially full. The concrete arch itself was not damaged, but one abutment was damaged. This canyon opens up to the northern part of the city of Los Angeles.

Pacoima Dam, a concrete arch structure, sustained damage to one abutment during the 1971 San Fernando earthquake; its reservoir was only partly full at the time.

Concern for the safety of dams and reservoirs has grown appreciably in recent years. The damage to Koyna Dam demonstrated that concrete gravity dams are not immune to earthquake damage, as had been presumed. This structure was designed in accordance with the then-prevailing standard practice in the United States. Similarly, the failure during the 1971 San Fernando earthquake of the earthen Lower San Fernando Dam, which nearly resulted in a disaster that would have affected tens of thousands of lives, was a dramatic reminder of the need for extreme safety in the design of dams located in populated areas.

As a result of these experiences, the California Division of Safety of Dams embarked on a program to evaluate the earthquake safety of existing dams in the state, and in 1972 the National Program of Inspection of Dams was authorized. Tragic failures (not caused by earthquakes) of the Teton Dam in Idaho in 1976 and of the Kelly Barnes Dam in Georgia in 1977 led to mounting national and congressional interest in dam safety and to the appropriation of funds for the inspection program.

Predicting the performance of concrete dams during earthquakes is one of the more complex and challenging problems in structural dynamics. The following factors contribute to this complexity:

- Dams and reservoirs are of complicated shapes, as dictated by the natural topography of the site.
- The response of dams may be influenced significantly by variations in the intensity and characteristics of the ground motion over the width and height of the canyon. However, for lack of appropriate instrumental records, the spatial variations of the ground motion cannot be defined with confidence at this time.
- The response of a dam is influenced, generally to a significant degree, by the earthquake-induced motion of the impounded water; by the deformability of the foundation rock, which invariably is fragmented by joints and fissures; and by the interaction of the motions of the water, the foundation rock, and the dam itself.
- During intense earthquake motions, vertical construction joints between monoliths may slip or open; concrete may crack; and the stored water may locally separate from the upstream face of the dam, resulting in cavitation. These phenomena are nonlinear and extremely difficult to model and account for reliably.

Major Research Accomplishments

The analysis and design of dams for earthquakes has progressed from empirical rule-of-thumb methods, through static force methods involving the use of seismic coefficients, to procedures that now recognize the dynamic nature of the problem.

Realistic analyses of the seismic response of dams were not possible until the development of the finite element method, recent advances in dynamic analysis procedures, and the availability of large-capacity, high-speed computers. Thus much of the research did not start until the mid-1960s, and the major advances were made in the 1970s. Initially, all nonlinear effects, including those associated with joint opening, concrete cracking, and water cavitation, were ignored, and the analyses either neglected or grossly simplified the interaction effects of the impounded water and foundation rock. Subsequently, special techniques were developed to incorporate the interaction effects and were used to analyze dams of different types.

The greatest success has marked the study of gravity dams, primarily because they are generally amenable to two-dimensional analysis. The reliability of the resulting analytical procedures has been established by demonstrating that they predict results that are generally consistent with the limited field observations—e.g., the earthquake damage experienced by the Koyna Dam, and the responses measured during forced-vibration tests on a limited number of dams in the United States. Parametric response studies have also made it possible to demonstrate the principal effects of interaction of the impounded water and of the foundation rock on the response of gravity dams.

Parametric response studies and analyses of the damage experienced by the Koyna Dam have revealed that the maximum stresses induced by severe earthquakes in concrete gravity dams may substantially exceed those predicted by traditional simplified design procedures. The discrepancy results from the failure of these design approaches to account for all important aspects of the problem. Improved design methods and criteria have recently been developed, but additional improvements are necessary before gravity dams can be designed with a high degree of confidence. Measurements of dam motions and water pressures during earthquakes are also required to corroborate the analyses.

The analysis and design of arch dams have not achieved the same degree of progress, primarily because these must be treated as three-dimensional systems. Substantial progress has recently been made in developing rational procedures for evaluating the hydrodynamic effects and for including the interaction effects of the impounded water. However, these procedures are not ready for practical application, because they cannot yet reproduce the true mechanism of transmission of the ground motion into the structure and because they entail excessive computational expense. Contributing to the difficulty is the fact that the spatial variation of the ground motion along the boundary of a dam cannot be defined reliably.

Analytical studies using available techniques have indicated that, during intense earthquakes, arch dams are likely to experience tensile stresses much larger than those predicted by present design procedures. During the 1971 San Fernando earthquake, a few arch dams experienced significant ground motion, and one of them, Pacoima Dam, was subjected to intense motion. Analytical correlations between the predicted and the actual performances of these dams were, unfortunately, severely limited by a lack of sufficient instrumental records of their response.

The current practice in the seismic analysis of concrete dams is to assume that the structure and its interaction mechanisms with the impounded water and foundation rock are linearly elastic. No calculations have yet accounted in a realistic fashion for the nonlinear effects associated with the opening of joints betwen monoliths. Analytically predicting the effects of concrete cracking has also proved difficult, because the failure criteria for mass concrete are not yet well established and because the results are sensitive to the assumed failure mechanism. Similarly, the effects of cavitation have received only exploratory studies.

Linear analyses do not adequately represent the true behavior of concrete dams during intense earthquake motions, and it is difficult to establish consistent design criteria only from the results of such analyses. A study of an arch dam model tested on the earthquake simulator of the University of California at Berkeley has recently produced some insight into the nonlinear response mechanisms involved.

The design of small-scale models to represent the behavior of large dams is fraught with difficulties. A principal value of the experimental study mentioned above is that it demonstrated the feasibility of testing arch dam models on presently available shaking tables. Larger shaking tables would naturally permit the testing of larger-size models, making it possible to simulate the behavior of a prototype structure better.

Benefits of Research to Engineering Practice

Federal and state agencies concerned with the construction of dams have revised their design standards to acknowledge the research accomplishments of the past decade. Static force methods involving seismic coefficients have given way to dynamic analysis procedures. The major dams in the California State water project (the Feather River project) were designed using dynamic analyses, which marked the first time that major dams were designed using modern methods based on the latest seismic research. The Bureau of Reclamation and the U.S. Army Corps of Engineers now also employ these methods in the design of dams, as do most countries with seismically active regions.

The design of major dams now employs the general methodology of earthquake hazard assessment, including seismotectonic investigations and the specification for design of ground motions and response spectra. However, because of the lack of adequate information concerning the dynamic strength and behavior of mass concrete under large cyclic strains, it is not yet possible to define reliably the conditions under which a proposed dam is likely to experience a specified degree of damage during an earthquake.

In response to growing public concern over the safety of dams and reservoirs, major federal dam-building agencies and states such as California and Utah have adopted programs for evaluating the safety of existing dams. Since most of these dams were designed using methods that are now considered overly simplified, there is considerable interest in reevaluating the original designs using current procedures. As a result of such safety evaluations, structural modifications have been made to some dams, and restrictions on reservoir water levels have been imposed in some cases. Since the economic impact of such modifications and restrictions is generally substantial, it is important to improve the reliability of present methods of safety evaluation.

Current Needs and Challenges

Although considerable progress has been made in the last decade, much additional research needs to be done to improve the reliability of present methods for the analysis, design, and safety evaluation of concrete dams. To meet this objective, the following tasks should be pursued:

1. Major dams in seismic areas of the United States must be instrumented to measure their responses during future earthquakes. The instrumentation should be designed to provide adequate information on the characteristics and spatial variation of the ground motion at the site, the response of the dam, and the hydrodynamic pressures exerted on the dam. Because of the urgent need for such data, dams in highly seismic regions of other countries should also be considered for instrumentation. This effort should be coordinated with the plans for the seismic arrays recently installed in Taiwan and now being planned for India and the People's Republic of China under cooperative agreements with the United States.
2. Forced-vibration tests should be conducted on selected dams at different water levels, and the resulting hydrodynamic pressures and motions of the structures and their foundations must be recorded and analyzed.
3. Existing analytical methods for computing the response of all types of dams to earthquakes should be refined, and their reliability should be assessed by comparing their results with the responses recorded during forced-vibration tests and actual earthquakes. These methods and the computer programs needed for their implementation should be developed in a form convenient for application in engineering practice.
4. Carefully planned parametric studies must be conducted to provide improved insight into the interaction effects of water and foundation rock. Special attention should be given to defining the conditions under which these effects are sufficiently important to warrant their consideration in design, and simplified design procedures must be developed for these cases.
5. Appropriate equipment must be developed for testing multiaxially loaded mass concrete specimens under cyclic deformations of the type induced by earthquakes, and comprehensive experimental studies should be undertaken to define the stress-strain characteristics and

strength of mass concrete better. From the results of such studies, constitutive models must be developed that can be incorporated into nonlinear response analysis procedures to predict the damage in dams due to a specified level of seismic excitation.

6. Dynamic tests must be conducted on models of concrete dams to investigate the effects of such factors as joint opening and water cavitation, which are not readily amenable to analysis.

7. Analysis procedures must be developed that can account for the effects of concrete cracking, joint opening, and water cavitation, and parametric response studies must be carried out to evaluate their importance. From the results of these studies and of the experimental program suggested in item 6, the conditions must be defined under which these nonlinear effects are sufficiently important to warrant their consideration in design, and appropriate design guidelines must be developed.

8. Static tests to failure must be conducted on large-scale models of dams, especially arch dams, to define their behavior in the range approaching failure.

9. The results of these studies should be used to evolve rational and practical methods for designing concrete dams to be built in seismic regions and for evaluating the safety of existing dams.

Liquid Storage Tanks

Description and Importance of Problem

Liquid storage tanks have always been important components of lifeline and industrial facilities. They are critical elements in municipal water supply and fire-fighting systems, yet in past earthquakes water tanks have collapsed or been so badly damaged as to be put out of service. Tanks containing water, oil, or chemical fluids serve many industrial processes. For instance, oil refineries have always used many petroleum storage tanks. In past earthquakes in the United States and Japan, damage to such tanks has caused the release of their contents and extremely destructive conflagrations.

In recent years the seismic safety of tanks has become even more important with their use as safety elements for nuclear reactors and to store liquefied natural gas. Furthermore, the large-scale importing of petroleum has brought an increased use of particularly large tanks. Steel storage tanks 300 ft in diameter and 60 ft high are being constructed for petroleum storage, and even larger tanks will probably be constructed in the future. These unprecedented structures will pose special problems of earthquake safety.

As the numbers and sizes of such structures have increased, so have

Many petroleum storage tanks were damaged and some collapsed during the 1964 Alaska earthquake. In several places fires burned for long periods after the earthquake. Many storage tanks are presently being constructed, some of unprecedented size. These must be analyzed and designed to be safe during expected ground shaking.

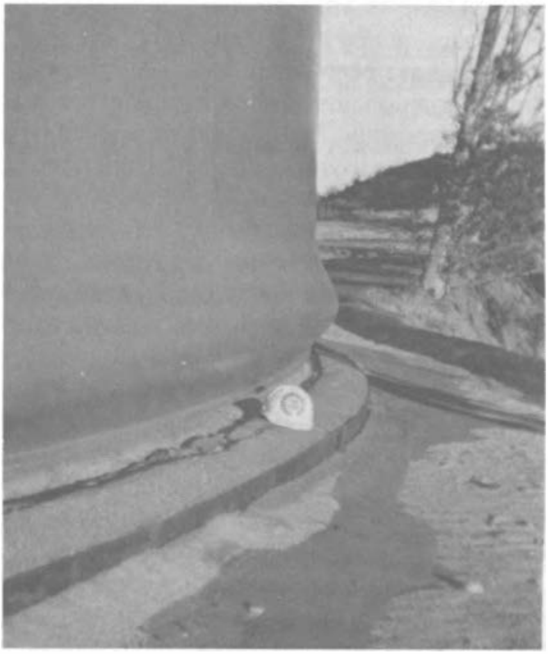
their importance and the need to understand better their response to seismic excitations. The value to society of these structures exceeds the economic worth of both the tanks and their contents. Depending on the stored product, failure of tanks or their accessories may lead to fires, pollution or contamination of surrounding areas, or water shortages. Their failure may also impede fire-fighting efforts at critical times.

In regions of very strong shaking in past earthquakes, many tanks have been severely damaged or have collapsed. But quantifying the adequacy or inadequacy of these tanks has been difficult, because neither the motions of the ground nor of the tanks have been recorded. This lack of earthquake records poses a difficulty in developing optimum seismic designs.

Some tanks have failed during earthquakes with disastrous consequences. For example, the fires that followed the 1964 earthquake in Niigata, Japan, caused extensive damage to two oil refineries. The failure of oil storage tanks in the 1978 earthquake in Sendai, Japan, polluted local waterways. The 1964 Prince William Sound earthquake in Alaska caused the failure of numerous oil storage tanks and fires, and the 1971 San Fernando earthquake in California led to the failure of several water tanks both above ground and below ground. In 1978 an earthquake near San Juan, Argentina, extensively damaged wine storage tanks, causing the loss of many millions of gallons of wine;

the economic impact on the area was substantial. Also, over 100 wine storage tanks were damaged in Livermore, California, during the Greenville-Mt. Diablo earthquake of 1980. Wine tanks consist of special materials and have other special features. Similarly, many kinds of specialized tanks are in use in industry, posing special problems of seismic design.

Tank damage or failure manifests itself in one of the following ways: (1) buckling of the shell, precipitated by excessive axial compression due to overall bending or beamlike action of the structure; (2) damage to the roof, caused by sloshing of the upper part of the contained liquid with insufficient freeboard between the surface of the liquid and the roof; and (3) failure of piping or other accessories, due to the inability of these elements to accommodate the deformations of the flexible shell. Shell buckling typically takes the form of diamond-shaped buckles or "elephant's foot bulges" that appear a short distance



During an earthquake a liquid storage tank is forced into movement. The contents of the tank develop a sloshing motion, which can produce unusual stresses in the wall of the tank. One of the first symptoms of damage is the "elephant's foot bulge" around the base of the tank, as shown in this photograph. Prolonged shaking causes the buckle to be further compressed, possibly leading to collapse.

above the base and usually extend around most or all of the circumference. Differential settlement of the foundation may also precipitate tank failures.

Major Research Accomplishments

Most of the past research on the seismic response of liquid containment structures has sought to elucidate the behavior of cylindrical ground-supported tanks subjected to horizontal ground shaking.

In early analyses of this problem, the tank was presumed to be rigid and anchored at the base. These studies have shown that the dynamic pressure exerted against the walls of the tank by the liquid may be described by assuming that part of the liquid near the free surface undergoes a long-period sloshing motion while the rest moves synchronously with the tank as a rigidly attached mass. The maximum acceleration experienced by the rigidly attached component of the liquid is clearly equal to the maximum ground acceleration, whereas the maximum response of the sloshing component depends on the history of ground motion and the dimensions of the tank itself. Simple practical procedures have been developed to determine the magnitudes of the two liquid components and to evaluate the magnitudes and distributions of the resulting hydrodynamic pressures. For tanks of ordinary proportions, the rigidly attached component of the liquid contributes the larger effects.

As steel storage tanks become larger, the deformations of their walls during an earthquake may have an important influence on their response. Recent research has also examined this problem. It has shown that the seismic effects in a flexible tank may be substantially greater than those in a similarly excited rigid tank, and procedures of varying degrees of sophistication have been developed to evaluate the effects of tank flexibility.

The foregoing analyses of tanks apply to structures that are anchored at the base. In practice many of these structures are unanchored, and under the influence of intense ground shaking they tend to slide or to lift off the foundation, leading to a nonlinear response that is difficult to evaluate. Some approximate procedures have been developed to estimate the maximum stresses induced in the walls of unanchored tanks, but none is based on a rigorous treatment of actual behavior. Improved methods of analysis must be developed and must be checked by comparing their results with the recorded responses of tanks during earthquakes.

In addition to analytical studies, several experimental studies have been conducted in recent years. These include ambient and forced vibration tests on full-scale water storage tanks; laboratory tests on small plastic tank models subjected to harmonic and random excitations at their bases; and tests, with simulated earthquake ground motions, of several aluminum tank models and of a full-scale wine storage tank of the type damaged during the 1980 earthquake in Livermore, California. These experimental studies have provided improved insight into the dynamic behavior of the types of tanks tested and have helped to clarify the limitations of present methods of analysis. In particular, they have shown that the response of unanchored tanks is highly nonlinear and considerably more complex than current design procedures presume.

Substantial differences between measured and predicted responses also were observed in the tests of anchored tanks. The measured responses revealed appreciable distortional oscillations of the cross section in addition to the nearly uniform, beamlike response predicted by the analysis procedures now in use. This distortional response has been attributed to the effects of initial out-of-roundness or irregularities caused by imperfections in fabrication. Exploratory analytical studies have been made to explain the origin of this unexpected response mechanism, but additional studies are needed to clarify the phenomenon involved and to determine the extent to which the irregularities of the test structures are representative of those actually found in practice.

Benefits of Research to Engineering Practice

The results of the research discussed above have been used in the design of the large-capacity liquid storage facilities constructed in recent years, and in general have substantially improved the design of tanks for earthquakes. The American Petroleum Institute and the American Water Works Association have adopted, in their design standards API 650 and AWWA D100, detailed rules for the seismic design of liquid containment structures, rules based on the research that has been done on the seismic response of tanks.

Current Needs and Challenges

Despite the progress made in recent years in understanding the seismic response of liquid containment structures, additional basic research is needed to improve the reliability of present methods of analysis and design. Listed below are some of the more important topics requiring study.

1. The greatest need concerns the behavior during intense earthquakes of tanks that are unanchored at their base. An improved analysis procedure is needed that properly accounts for the effects of sliding and uplifting of the base and that reproduces with a reasonable degree of accuracy the complex nonlinear response mechanisms that experimental laboratory programs have revealed. Comprehensive par-

ametric studies of the response of such structures are also needed, using both refined and simpler approximate methods of analysis. Such studies should seek to assess the effects and relative importance of the numerous factors that influence the response; identify the factors and aspects of response that dominate the design of the structure; and, on the basis of this information, formulate improved approaches to design.

2. A better understanding is needed of the buckling of the walls of a liquid containment structure under dynamic conditions of loading, and of the effect of such buckling on the overall integrity of the tank. Both experimental and analytical studies should be conducted to define dynamic buckling sufficiently well that the design process can take it into account.

3. Additional experimental and analytical studies are needed to clarify the origin and practical significance of the distortional vibrations of the tank cross section revealed in some laboratory tests. Studies of the behavior of anchored tanks would be particularly promising in this respect. Because this distortional response arises, at least in part, from the effects of initial out-of-roundness or irregularities, an effort should also be made to define the magnitude and distribution of such irregularities in actual structures.

4. In evaluating the effects of liquid sloshing, the amplitudes of motion at the free surface of the liquid are considered to be sufficiently small that the response is linear. The influence of nonlinear liquid sloshing should be investigated, particularly as it affects the integrity of the tank and roof. The possible effects of cavitation, caused by the liquid periodically losing contact with a portion of the tank wall, should also be considered.

5. Studies of the seismic response of liquid storage tanks normally neglect or approximate the effect of the vertical component of ground shaking. Except for some recent exploratory studies, this problem has not attracted the attention it deserves. A rational method should be developed for evaluating the response to vertical excitation.

6. Another factor requiring study is the influence of soil-structure interaction both for laterally and vertically excited systems. An important by-product of such a study would be an evaluation of the damping appropriate to the various modes of vibration of tanks.

7. A realistic evaluation of risk should also be made for large-capacity tanks containing liquid gases, such as liquefied natural gas, liquefied petroleum gas, or ammonia. The unique features of these structures' design are the interaction of the double shell through a common base and the influence of the insulation and of elevated pile caps.

8. In view of the increased interest expressed in recent years in using liquid storage facilities offshore, there is a need for improved

understanding of the seismic behavior of submerged tanks of various shapes. The seismic behavior of tanks that are partially or fully buried in the ground, and of tanks containing granular materials, also requires study.

9. For each class of structure considered, a range of properly planned and executed field tests on full-scale structures is needed to assess the adequacy of analytical predictions and to help guide future analytical developments and laboratory test programs. Finally, and very importantly, a reasonable number of tanks in seismically active regions should be instrumented to provide controlled data on their behavior during actual earthquakes.

Offshore Structures

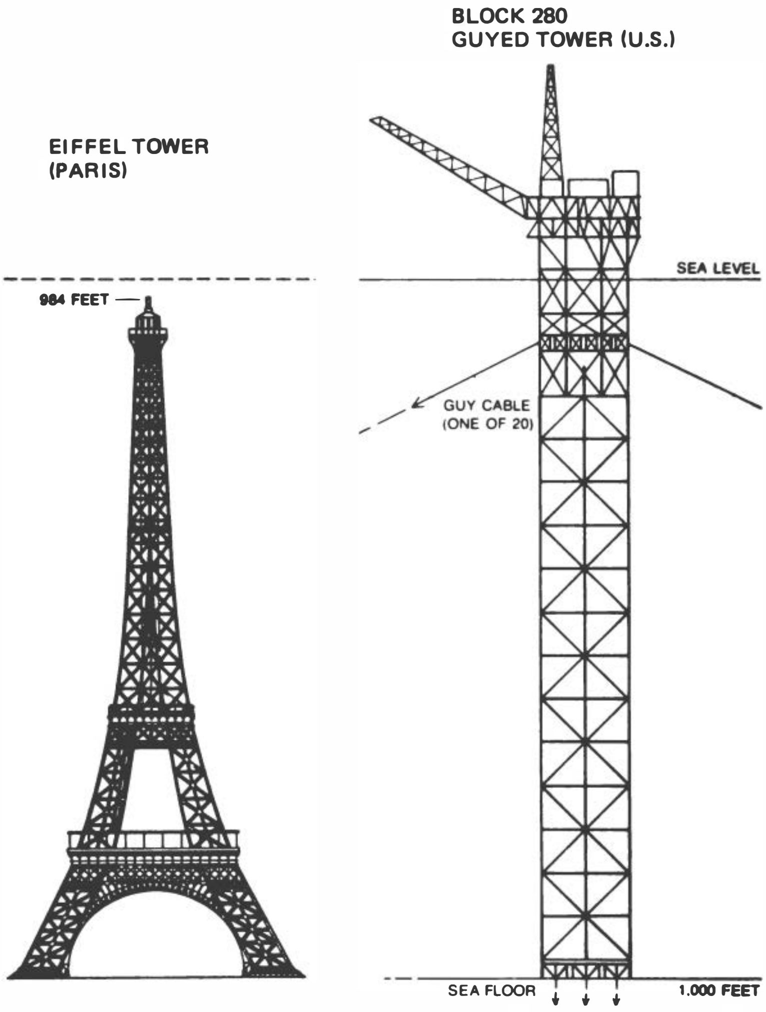
Description and Importance of Problem

Offshore structures are a critical element in the development of domestic and international energy resources. There are now some 4,000 major and 5,000 minor bottom-supported platforms in the world's oceans and lakes. About 4,000 of these are in coastal waters of the United States, some in seismically active regions. About 25 percent of the United States' oil and gas at present comes from offshore areas. By the year 2000 this figure is expected to increase to 35 or 40 percent, with production extending to water depths of several thousand feet. The move to progressively deeper waters will require the further development and implementation of new concepts of platform design. Since many of these structures will be located in regions prone to earthquakes, it is essential that proper attention be paid to their earthquake safety.

Offshore platforms are space frames built mainly of steel, although a number of major concrete platforms have also been built. The steel structures generally consist of welded tubular members, and their foundations typically consist of tubular piles with diameters of up to 10 ft extending to depths of up to 600 ft below mudline. The dynamic behavior of these structures, particularly in the postelastic and yielding ranges of deformation, differs significantly from that of building structures. Thus great care should be exercised in transferring design experiences from one class of structure to the other.

The following additional factors contribute to differences in the seismic performance of buildings and offshore structures:

- The magnitudes and distributions of mass and stiffness for offshore platforms differ substantially from those for buildings. In particular, the heavy concentration of mass on the deck of an offshore platform



This schematic drawing shows a comparison between an offshore structure, in 1,000 ft of water, and the Eiffel Tower. Towers are now being designed to stand in up to 1,500 ft of water in seismic regions. Besides resisting regular operating forces, these structures must also withstand wave forces and earthquake forces. These requirements pose unprecedented engineering design problems whose solutions depend heavily on special seismic and hydrodynamic research. From "Advanced Offshore Oil Platforms" by Fred S. Ellers. Copyright © 1982 by Scientific American, Inc. All rights reserved.

accentuates the similarity of its action with that of an inverted pendulum.

- The effects of the surrounding water, particularly its interaction with the vibrating platform, have no counterpart in the response of buildings.
- Deep-water platforms are now being considered for water depths

of 2,000 to 6,000 ft. These are highly flexible, compliant structures with fundamental natural periods of vibration in the range of 25 to 100 seconds. The design of such structures presents a host of special problems.

- Because offshore platforms are designed for storms that, like earthquakes, induce large lateral forces, the incremental lateral strength required for earthquake resistance is generally not as great for offshore structures as it is for buildings.

The development of earthquake-resistant design for buildings has benefited from extended observations of the performance of many and different types of such structures during earthquakes of damaging intensity. Because of the relative youth of the offshore industry, however, offshore structures lack comparable experience. As a result, the seismic design of these structures has had to rely on analyses and the results of experimental laboratory studies, which emphasizes the importance of basic and applied research. Observations of offshore structures during intense storms have yielded some valuable insight into their strength. However, because the characteristics of the forces induced by waves and earthquakes differ, additional research is needed to delineate the interrelationship of the structural resistances to these two forms of dynamic excitation.

Major Research Accomplishments

The last decade has brought a significant development of knowledge about the response of offshore platforms to earthquake ground motions, knowledge that has been applied to the seismic analysis and design of such structures. For example, the 900-ft-tall Hondo platform of the Exxon Company offshore of Santa Barbara, California, was analyzed and designed using the latest research results. Other offshore structures in the United States and other parts of the world have received similar analysis and design.

Experimental and analytical studies have provided improved insight into the characteristics of seafloor soils and their response to intense earthquake ground motions. Some progress has been made in defining the seismicity of the coastal areas of the United States, and methodologies have been developed for estimating the intensity and characteristics of the ground motions that can be expected at specific sites. The development of instrumentation for measuring earthquake ground motions at sea floors has also made some progress.

The performance during earthquakes of piles and pile-supported structures is of paramount importance to the offshore industry, and this topic has been the subject of numerous studies. Despite the progress made, however, this problem remains among the high-priority issues requiring additional study in the years ahead.

A number of laboratory test programs have evaluated the strength and deformational characteristics of tubular members and of assemblages of such members. Axially loaded members, members in bending, and members undergoing combinations of bending and axial forces have been investigated, with particular emphasis on their behavior in the inelastic and postbuckling ranges of deformation. The test programs included two one-sixth scale models of an X-braced offshore platform; they were tested quasistatically with loading patterns that simulated the effects of intense earthquakes. The results of these studies have helped to identify the parameters that control the strength and behavior of tubular members and frames composed of such members. They have also made possible the development of algorithms for modeling the way in which members undergoing large cyclic deformations degrade. Finally, simple design rules have been formulated to define the properties of members that are required to ensure desired performance in the postelastic range.

The methods of nonlinear dynamic analysis of structures referred to in Chapter 6 have been adapted to computing the response of platforms in the postelastic ranges of deformation, with computer programs of wide versatility having been developed. These programs can provide for the types of structural and foundation nonlinearities that are of interest in the design of offshore structures and for the effects of fluid-structure and foundation-structure interaction.

A model platform structure, approximately one-tenth scale, representing a platform designed for use in the offshore region of southern California has been tested dynamically on a shaking table. Besides demonstrating the performance and failure mechanisms of the structure during damaging earthquake ground motions, this test has provided data that can be used to assess, and if necessary improve, existing analytical procedures for predicting the seismic response of offshore structures.

Benefits of Research to Engineering Practice

The developments outlined above have made possible the design of reliable and cost-effective platforms in earthquake-prone regions. The development and updating of the following design guidelines and codes have been of major value in this regard:

- The American Petroleum Institute's *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms* (API RP 2A).
- The American Concrete Institute's *Guide for Design and Construction of Fixed Offshore Concrete Structures* (ACI 357).
- The U.S. Geological Survey's requirements for design of fixed offshore structures.

For major structures, site-specific studies are made to determine the intensity and characteristics of the design earthquake ground motion. This approach considers the active faults in the region, the type of faulting, the maximum earthquake magnitude that each fault could generate, the rate of seismic activity in the region, the proximity of the site to the faults, and the soil conditions at the site. The platform is designed to experience no damage from earthquakes with intensities that have a low probability of being exceeded over the life of the structure, and to have enough capacity to absorb energy to prevent collapse from a rare extremely intense event.

The recent improved understanding of the seismic response of offshore structures has also been valuable in the design of these structures to resist wave forces.

Current Needs and Challenges

Continued leadership in the development of the structures needed to exploit the energy and mineral resources of the continental shelves and slopes will require further progress in each of the following areas:

1. Inexpensive and reliable instrumentation systems must be developed to measure the response of seafloor soils to strong ground motions, and these must be deployed to evaluate seismic activity in offshore areas. In addition, increasing numbers of offshore structures and their foundations must be instrumented to measure their response during earthquakes, and these results must be correlated with those predicted by current methods of analysis.
2. Unlike the response of a stiff structure such as the containment structure for a nuclear reactor, which is controlled by the high-frequency components of ground motion, the response of offshore structures, particularly those now considered for future applications, is dominated by the long-period components of excitation. These long-period components should be investigated, along with their influence on the response of flexible systems. Simple procedures must also be developed to define reliably the characteristics of response spectra in the long-period region for both linear and nonlinear systems subjected to earthquakes.
3. With the aid of available computer programs, parametric studies of the seismic response of representative platforms should be carried out to improve the understanding of their behavior under intense excitations. The results of such studies should then be used to formulate simplified design guidelines and methods that can ensure desired performance in the postelastic range. The effects of fluid-structure and soil-structure interaction should receive due attention.
4. The studies referred to in the preceding item should be supplemented by basic experimental and analytical studies of the behavior

of component elements to further improve their representation in analysis. Topics requiring additional research include the postelastic and yielding behavior of tubular members and joints, the behavior of soil deposits under intense motions, the behavior of piles and pile foundations, the interaction of piles and the superstructure, and the interaction of the structure with the surrounding liquid.

5. The dynamic behavior of piles and pile foundations is probably one of the most important topics requiring further study. Their performance should be investigated experimentally and analytically, considering both low-level excitations and excitations of high intensity, for which nonlinear effects become important. The ultimate objective should be to develop simplified procedures for defining their stiffness and damping for each principal mode of deformation.

6. The guyed tower, which is effectively a space frame pinned at the base and laterally supported by cables, and the tension leg platform, which is essentially a semisubmersible structure anchored to the sea floor by pretensioned vertical members, are concepts of platform design that are now finding application. Economically attractive for water depths beyond 1,000 ft, these structures are highly compliant, and their dynamic response is significantly influenced by geometric nonlinearities that are of minor consequence in the design of much stiffer structures. The seismic behavior of these structures should be investigated, starting with the simplest possible idealization of the problem and proceeding systematically to more realistic, complex representations.

7. The seismic behavior of important auxiliary systems such as pipelines, well conductors, risers, tethers, and deck-supported equipment has received little attention. Systematic studies of these components are needed to improve the overall reliability of the design of offshore systems.

8. The approaches used in the design of offshore structures for waves and for earthquakes have developed along different paths over the years. The interrelationships of the two approaches should be clarified so that design experiences can be transferred from one area to the other. Such studies should ultimately lead to a unified approach to design for both waves and earthquakes.

Tsunamis

Description and Importance of Problem

Tsunamis are long water waves generated by large-scale tectonic displacements of the ocean bottom during an earthquake. Such waves can also be generated by large underwater landslides triggered by earthquakes, or by large volcanic eruptions such as Krakatoa. In all of these cases, the scale of the generating mechanism is so large that the waves can be measured for several days on tide gages throughout an entire ocean.

This section also considers inland events, as they may generate waves that are large enough to be important in a local region, such as a lake or reservoir. They may be generated by fault displacements, rapidly moving underwater earth or mud slides, slumping river deltas, or high-speed rockfalls into a body of water.

Past earthquakes in Alaska, Japan, and western South America have demonstrated the potential destructiveness of tsunamis, and in coastal regions the tsunami hazard must be considered for earthquake preparedness. However, the present state of tsunami hazard assessment is not adequate, and a better understanding of the hazard is needed along the west coast of the United States.

The leading waves of tsunamis move across oceans or other bodies of water at relatively high speeds, approximately $(gh)^{1/2}$, where g is the acceleration of gravity and h is the water depth. They are refracted and diffracted by the bathymetry, by islands, and by other major geographic features. They may become trapped on a continental shelf. They may induce ''resonant'' motions within bays and harbors. They run up onto land, and they cause substantial drawdown, sometimes exposing the bottom to a much greater extent than occurs during low tides. If the source motion is downward, a substantial drawdown may occur before a run up.

Owing to the often relatively high velocities of the water, life is lost, buildings are damaged or destroyed, bottom scouring occurs, boats are grounded, and ship moorings are broken. Other effects, such as failures of seawalls or possible loss of cooling water for thermal-electric power plants at ocean intakes, might also occur during major drawdowns.

Table 6 presents some estimates of the loss of life and economic damage from tsunamis within the United States since 1946. Much greater loss of life and economic damage has occurred in other countries throughout history. For example, in 1896 a tsunami generated near Japan caused the loss of nearly 22,000 lives in the Sanriku District of Japan, and in 1933 about 3,000 people were killed in the same region by a tsunami resulting from a major nearshore earthquake. In addition, Japan has been seriously affected by distantly generated tsunamis such as that from Chile in 1960.

Major Research Accomplishments

The National Science Foundation sponsored a workshop on tsunamis in 1979. The worskhop report summarizes much of what has been

TABLE 6 Major Tsunamis Affecting the United States Since 1946

Date	Places of Major Impact	Location of Source	Tsunami Fatalities	Tsunami Damage (millions of 1980 dollars)
1946	Hawaiian Islands	E. Aleutian Islands	173	119.2
1952	Hawaiian Islands	Kamchatka	0	2.1
1957	Hawaiian Islands	Aleutian Islands	0	10.5
1960	Hawaiian Islands	S. Chile	61	66.9
1964	Alaska, N. California, Hawaiian Islands	Prince William Sound, Alaska	119	282.3
1975	Hawaii	Hawaii	2	4.2
TOTAL			355	485.2

SOURCE: National Science Foundation and National Oceanic and Atmospheric Administration, *Tsunami Research Opportunities: An Assessment and Comprehensive Guide*, National Science Foundation, Washington, D.C., September 1981, 50 pp.

learned through research during the past decade.*

Numerical models of tsunami generation by hypothetical source mechanisms consisting of tectonic displacements have undergone major advances. It appears that this problem has been solved *in principle*, and for relatively simple sources it has been solved in practice. Geologists and seismologists have made much headway in advancing the understanding of the details of fault mechanisms and the characteristics of the ground motions that generate oceanic-scale tsunamis.

Numerical models have been developed that can now be used to calculate the propagation of tsunamis across an ocean, and these appear to be reasonably good. Nonlinear effects are practically nonexistent in the deep ocean. However, as the waves travel over the continental shelf and into nearshore waters, nonlinear effects may become quite important. Nevertheless, considerable advances have been made on the problems of wave transformation in coastal waters, the response of bays and harbors to tsunamis, numerical methods for studying the diffraction of long waves, and to a lesser extent the run up and drawdown on tsunami waves at the shore.

Benefits of Research to Engineering Practice

The research accomplishments mentioned above have led to the development of first-generation numerical models, which have been

---

*Li-San Hwang and Y. Keen Lee (eds.), *Tsunamis: Proceedings of the National Science Foundation Workshop, May 1979*, Tetra Tech, Inc., Pasadena, California, 1979.

used to predict probable run-up elevations on land along the Pacific Coast of the United States and Hawaii, at least for tsunamis generated at a distant source. However, they have not yet been tested sufficiently in either the laboratory or the field.

With regard to tsunami risk analysis, the data in the major extensive historical catalog of tsunamis, which was developed in the late 1960s, are being added to by other publications. Such tsunami catalogs are useful in assessing the type and extent of damage that can occur at many locations. They are also helpful in providing dates of occurrences to engineers searching local newspapers and other accounts for information on tsunamis. Also, through the World Data Center Systems, the National Oceanic and Atmospheric Administration (NOAA) manages an ever-growing tsunami data base that is of considerable benefit to engineers in determining the types and degree of problems that tsunamis can cause.

The operation of the Tsunami Warning System has been improved, which will help local authorities decrease the loss of life during future tsunamis.

By understanding the mechanisms related to resonance in bays, significant tsunami protection works have been designed in Japan, such as the tsunami breakwater at Ofunato, Japan. Such facilities have made certain key sections of the coast safer than before from inundation by tsunamis.

Current Needs and Challenges

NOAA and the National Science Foundation cosponsored a planning workshop near Seattle, Washington, in August 1980. Table 7 gives a brief summary of the workshop's conclusions and priorities for research that should be done in the future.

In addition to the research recommended above, other work is needed. For example, the accuracy of present numerical models must be tested, especially with regard to their predictions of run up and drawdown elevations. Also, the problem of small-scale tsunamis, which may be of great impact in local areas, has not been studied in a major way. In this case complicated details of the geometry of the site are important, and three-dimensional numerical models need to be developed, along with physical models to test these numerical approaches. Little is known of several types of source mechanisms, such as underwater slides, slumping, and soil liquefaction caused by earthquakes; both model and prototype studies are needed. Depending on the kind of source, large initial drawdowns may occur, and these too need to be studied, because in the nonlinear case they behave differently than do initially positive sources.

It will be difficult to do much of the needed research with the limited

TABLE 7 Tsunami Research Plan Priorities

Need	Proposed Efforts	Priority	Research Area
High	Tsunami Observation Program Design and install instruments to measure (1) tsunamis along the coastline, (2) tsunamis in the open ocean.	I	All areas
High	Modeling and Design Related to Terminal Effects (1) Establish theoretical and laboratory program for fluid-structure interactions; (2) determine structural design criteria.	II	Terminal effects
High	Tsunamigenic Earthquake Identification Establish a coordinating body of federal agencies to examine seismic characteristics of tsunamigenic earthquakes.	II	Instrumentation/ Tsunamigenic earthquakes
Moderate	Tsunami Data Set Creation Increase and verify existing data sets and use in risk analysis.	III	Social response/ Risk analysis
Moderate	Emergency Preparedness Program Development Create public awareness program of potential dangers of tsunamis.	III	Warning

SOURCE: National Science Foundation and National Oceanic and Atmospheric Administration, *Tsunami Research Opportunities: An Assessment and Comprehensive Guide*, National Science Foundation, Washington, D.C., September 1981, 50 pp.

resources available. Many of the existing research facilities in the United States have been allowed to deteriorate, with respect to both equipment and personnel. In addition, there is a great need for a very large physical model facility to study a number of the very difficult problems of tsunami wave action at a coast, especially near-field wave motions where the source mechanism is near a coastal site. This facility is needed to check the validity of numerical models, to develop insight into the physics of the problems, and to perform model tests of specific sites that have complicated geometries or source mechanisms.

There is a need to examine or reexamine the data and studies made of the damage caused by tsunamis, and to classify the remedies or limitations. A properly constituted team of engineers should also investigate and prepare reports on damage done by future tsunamis.

Improved methods of tsunami hazard assessment are needed. Destructive tsunamis can be generated near the affected coast or thousands of miles away, and both of these possibilities must be considered in hazard assessments for the west coast of the United States.

9

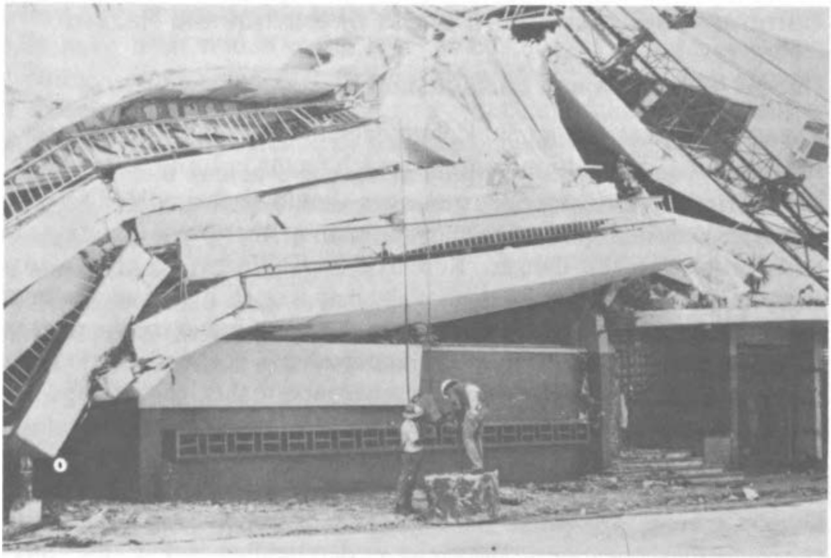
Social and Economic Aspects

Destructive earthquakes have severe impacts on societies. The 1976 Tangshan, China, earthquake destroyed this industrialized city of 1,500,000 people, killing several hundred thousand; the 1906 San Francisco earthquake and consequent fire destroyed a large section of the city; the 1972 Managua earthquake killed over 6,000 people, and the economic loss equaled Nicaragua's gross national product. Such great disasters occur not only because of a large earthquake, but also because of poor earthquake preparation.

The fruits of earthquake engineering research are of value to a community only when they are used. Social, economic, and political factors are critical in determining where and when this use occurs. For example, the fate of proposals to strengthen or demolish seismically unsafe structures in Los Angeles and San Francisco hinges on a poorly understood complex of social and economic issues. The complex includes the relative power of interest groups, the public interpretation of private property rights, the anticipated effects on opportunities for neighborhood employment, public conceptions of urban aesthetics, and the differential impact of these proposals on racial, socioeconomic, or age-group minorities. Making wise choices among contending engineering solutions to problems of hazard mitigation may depend as much on understanding social and economic factors as on assessing engineering feasibility. This chapter examines what has been learned and what needs to be learned about social and economic factors that affect the use of, and should affect priorities in, earthquake engineering research.

During the last decade the awareness of earthquake hazard has grown considerably. Twenty years ago the public had very little awareness of the earthquake hazard, state and local governments had not much more awareness, and even the federal government seemed unaware of earthquake hazards. Now the federal government is concerned; some state and city governments are studying the problem; and newspapers, magazines, and TV programs devote considerable attention to earthquakes and their hazards. This awareness and interest in earthquakes can be attributed to writings that developed from relevant research, to lectures by research workers to public groups,

This hospital building in the city of Tangshan, China, collapsed after the earthquake of July 28, 1976. A magnitude 7.8 earthquake centered under this industrial city of one million people created one of the greatest earthquake disasters in history. Eighty five percent of the buildings either collapsed or were severely damaged, and several hundred thousand people were killed. Earthquake-resistant design was not required by the building code, so the city was almost completely unprepared. A visit to the city in September 1982 revealed that a strenuous rebuilding effort was under way. The other 39 provinces had been called upon to provide engineering, architectural, and construction services and materials. Reportedly, four years after the earthquake a sufficient number of apartment houses had been constructed to accommodate about half the population.



This six-story building collapsed during the 1972 Managua, Nicaragua, earthquake. This earthquake, which was centered in the city, caused extensive damage and over 6,000 deaths. The damage loss was estimated to have been equal to Nicaragua's gross national product and thus had a great social impact.

business clubs, and groups of government employees, and to destructive earthquakes occurring in the world.

Systematic study by the social sciences of earthquakes can principally be dated from the Alaska earthquake of 1964. Much more is known about the social and economic aspects of natural hazards that recur more frequently, such as tornadoes, hurricanes, and floods. Responses to earthquakes and earthquake threats can often be inferred from a knowledge of responses to other hazards. But earthquakes are sufficiently different that such inferences can only be tentative. Japan and the United States are the leaders in this research, with contributions from Italy, West Germany, China, Central America, and Australia.

This chapter divides the problem into five areas: communication and awareness of earthquake hazard; household, neighborhood, and community response; economic aspects; governmental and legal aspects; and differential impact and response among segments of the population. The discussions of each area must keep in mind four kinds of time periods—periods of quiescence between important earthquakes, periods following an earthquake prediction or warning, periods of impact and immediately after impact, and postearthquake periods of reconstruction. Each period will not always be treated separately, but it must be remembered that problems and solutions often vary from stage to stage.

Communication and Awareness of Earthquake Hazard

Hazard Mitigation and Earthquake Forecast

The effectiveness of communication depends on both the message and the medium. This section considers each factor in turn.

In periods before a quake, messages should be formulated so as to convey a realistic sense of earthquake risk, neither overestimating nor underestimating the danger. Research in California has revealed a common pattern in news on earthquake risk: it starts by sensationalizing the danger and concludes with reassurances that minimize the danger, rather than offering a consistent and realistic account. Earthquake scientists and engineers often complain about the inaccuracies and distortions introduced by newspapers and TV stations when presenting information to the public. Also, because of public unfamiliarity with scientific concepts such as probability, scientifically unimpeachable announcements are often grossly misunderstood. This observation raises further questions: How can understanding rather than mere familiarity be conveyed, and how much understanding is realistically achievable or necessary? For example, a year after the first announcement of the southern California uplift (or Palmdale bulge), the majority of the Los Angeles County residents who had heard of the uplift either did not connect it with the possibility of an earthquake or were convinced that such an earthquake posed no danger where they lived. In recent years misleading predictions of impending earthquakes have generated much confusion. Both in Japan and the United States, and also in China, injudicious accounts in the news media about earthquake predictions have needlessly aroused public concern. Even international predictions have been made and publicized, as when a Russian seismologist predicted a large earthquake for California, or when a U.S. geophysicist predicted a disastrous earthquake for Peru. Recently, a U.S. National Earthquake Prediction Evaluation Council of reputable seismologists and geologists has been formed whose function is to evaluate predictions scientifically for the benefit of government agencies and, incidentally, the public. Unfortunately, it is still not clear how best to deal with such predictions.

If communication is intended to foster household preparedness or encourage activities to mitigate public hazard, the question is how to devise and disseminate messages that lead to action rather than passivity or fatalism. Behavioral research has demonstrated that an optimal balance between warnings and explanations of what can be done is needed to foster action.

There is much to be learned about the timing and programming of messages. Occasional public discussions of ways to enhance earthquake safety often make people suspect that danger is more imminent than they have been told. On the other hand, no one is sure how long "routine" announcements can be continued before they are ignored. A closely related question concerns whether a false-alarm effect is likely to follow a prediction or warning that subsequent events do not confirm. While limited evidence in both the United States and Japan suggests that this danger is exaggerated, research has not yet provided enough evidence to guide public officials in timing public discussions of earthquake hazard mitigation.

The media also face problems in transmitting information about earthquakes. They must seek to disseminate information so as to ensure that messages reach all relevant segments of the population on a timely basis and without distortion. Behavioral research has shown that the most effective communications begin with the mass media and are then filtered through discussion in organizations, families, and informal groups. Preliminary earthquake research suggests that reliance on the mass media without interpersonal discussion is associated with minimal understanding and inaction, that excessive reliance on interpersonal discussion is associated with unproductive levels of fear, and that a balanced combination is associated with constructive responses. Accoring to public opinion research, local "opinion leaders" or "folk experts" play a crucial role in fostering and guiding the interpersonal discussions. People who number a "folk earthquake expert" among their associates tend to be better informed about earthquakes than people who do not. But these folk experts are few in number. More needs to be known about who these folk experts are and how their numbers can be augmented.

Although people assign more credibility in earthquake matters to the mass media than to interpersonal communication, periodic waves of rumor are a problem that calls for better understanding. Evidence from both behavioral and earthquake research in Japan and the United States suggests that rumor often fills an information gap left when the mass media fail to address public concerns directly enough. Research is not sufficiently advanced, however, to give decision makers in the media much help when they are torn between the possibility of inadvertantly fueling a rumor by acknowledging and airing it and the fear of fostering it by ignoring it.

The study of public awareness complements the study of communication. Evidence from California and Japan indicates no lack of awareness of earthquake danger in general terms, though less is known about awareness in other earthquake-prone regions of the United States. The earthquake threat for Californians, though they show little evidence of denial or bravado, is low in their hierarchy of concerns. The Japanese, in contrast, hold it more salient. But awareness is selective: Californians appreciate the danger from old buildings collapsing and from being on or near a fault, but they show little awareness of the danger of living below a dam of unknown seismic resistance. Why such differences in awareness and preoccupation occur needs to be investigated.

In California, understanding what to do at the moment of an earthquake appears to be more prevalent than understanding how to prepare a household for an earthquake or what measures of earthquake engineering are needed for hazard mitigation. The drama of the moment—real and imaginary—may foster learning, but the understanding of conditions that foster learning is, again, woefully inadequate.

Science and technology, which are merged in popular understanding, command great awe and respect and are often credited with magical capabilities. But American research shows that most people adhere to a mixture of scientific and nonscientific beliefs, which affects the way they interpret earthquake danger and hazard mitigation.

People receive many earthquake forecasts and notices of specific kinds of danger, some of which they take seriously, most of which they do not. Personal experience of loss or injury in an earthquake inclines people to take warnings seriously; other kinds of earthquake experience do not. Popular decision making on matters of risk does not follow an exacting model of rationality, but may conform to some poorly understood model of weak or ''satisficing'' rationality. A better understanding of such popular decision models would help the design and implementation of programs to mitigate earthquake hazards.

Postimpact Communication and Awareness

After an earthquake the disaster overloads whatever communication facilities remain operative. Victims and outside relatives and friends try to make contact. Facilities are strained even more when a disaster strikes without warning and when families are apart. Because electricity is usually cut off, officials must issue information and directives to victims via loudspeakers, battery-operated radios, and door-to-door contact. Effective evacuation orders require all these modes of communication. Most residents are skeptical of nonvisible or unfamiliar threats, such as the possiblity of dam failure or tsunami. In addition to specifying routes, locations of shelters, travel times, and the like, evacuation orders should also tell evacuees to take important papers, personal valuables, and sufficient daily supplies. Otherwise evacuees are tempted to return to collect the forgotten items. By using the full range of communication modes, San Fernando area officials in 1971 achieved an impressive initial evaucation rate of over 90 percent within a few hours below the damaged Lower San Fernando Dam. But there, as often happens in Japan, many residents returned prematurely.

After most disasters victims complain that they do not know enough about, or participate enough in, reconstruction plans that local private and public organizations and federal agencies typically formulate. Victims occasionally form citizens' committees to voice their demands to local government.

During the period of emergency following a disaster, interorganizational communication is hampered in countless ways: agencies typically strive to preserve their autonomy; they often cling to standard operating procedures that are inappropriate for emergency operations; law enforcement operations are overconcentrated on security; communication channels are overloaded; the necessary decentralization of agency operations to lower-echelon personnel multiplies communication errors and redundancies; with too little information, organizations tend to overestimate damage and request too much aid; and few communities provide a unified information center through which agencies and the media can share data and coordinate actions. This became quite apparent during the crisis at the Three Mile Island nuclear power plant.

Communication and coordination are further hindered when overlapping or multiple municipal and county jurisdictions are involved. The overlapping of jurisdictions had a considerable effect on relief and rescue operations after the moderate San Fernando quake. A community could be paralyzed after a great quake affecting a large and jurisdictionally varied area.

In some metropolitan communities, including Los Angeles, hospitals are well equipped to coordinate the distribution of patients via their Hospital Emergency Access Radio system (HEAR). But few financial and industrial enterprises are prepared to cope with a telecommunications breakdown. Little is yet known about the problem's magnitude, about ways to prevent it, and about ways to manage it after an earthquake.

These common observations from a wide range of disasters underline the need for careful research comparing more and less successful communication and coordination during and after crises. A better understanding of the crisis period should help to identify the problems most susceptible to engineering solutions.

Household, Neighborhood, and Community Response

Hazard Mitigation and Earthquake Forecasts

Communication and awareness are only means toward achieving a constructive response, such as home safety inspections, support for public expenditures to make public buildings safer, and adoption of stricter building codes. In California, individuals have done little to prepare themselves and their households for a destructive earthquake, and they express support for vigorous hazard mitigation activities by government without working to promote it. More citizen involvement is reported in Japan.

To implement home safety inspection programs and other household earthquake precautions, some kind of neighborhood organization is probably required. In southern California, but less so in northern California, grass roots organizations have been ephemeral and ineffectual in most instances. Neighborhood organizations that persist and have measurable effects generally adopt earthquake safety as an auxiliary service for some other overriding purpose or have been sustained by an established organization. In Japan strong leadership by the government has been crucial. By better understanding how a network of neighborhood organizations that foster earthquake preparedness can be maintained, the prospects for implementing hazard mitigation measures can be strengthened.

The most impressive grass roots mobilizations in the United States have resisted rather than supported certain earthquake hazard mitigation measures, such as draining an unsafe reservoir, designating a fault area as a ‘‘study zone,’’ and requiring landlords to upgrade seismically unsafe low-cost housing. This resistance seems to come partly from the material and symbolic costs of the measures to the community, from populist resentment against measures imposed by authorities from outside the community, from gross differences in perceptions of the situation and the risks involved, and from the often unjustified fear of decreased property values and other economic loss. To apply engineering knowledge successfully in such situations, a great deal more must be known about the causes for resistance and about the dynamics of grass roots mobilizations.

Postimpact Response of Individuals and Households

While victims of earthquakes commonly report feeling ‘‘shock’’ just after the event, their typical behavior is fairly rational: they check on the welfare of family members, get outdoors, take further precautions, volunteer for work, and administer first aid. Panic is usually confined to entrapped groups of strangers, and only truly traumatic experiences are known to evoke acute anxiety or depression, and then only in some people. In the San Fernando earthquake the greatest traumatic effects were observed in children, who were slow to recover, and in dogs that tended to run wild. People left homeless or without utilities often evacuate voluntarily, usually staying with relatives and friends nearby, but are anxious to return as soon as possible.

Research on a variety of American natural disasters indicates that victims organize themselves into "emergent" neighborhood groups to begin light rescue and cleanup operations, as well as to exchange emotional support and material necessities generously. This "altruistic" or "therapeutic" community is most cohesive and cooperative, and its mood is "highest," in previously cohesive neighborhoods and after disasters that seriously disrupt community routines but spare enough lives to preserve the social fabric. In some respects, the reaction of victims in the 1971 San Fernando earthquake was atypical. The therapeutic community was reputedly less strong, and victims got along better with disaster relief agencies. Whether these differences were caused by the evacuation experience, the urbanity and moderately high socioeconomic status of most victims, the relative normalcy in the surrounding metropolis, or the improved techniques employed by relief agencies is unknown.

Altruistic concern extends to the region and nation when publicly donated goods and outside volunteers converge on the disaster zone. While victims appreciate this outpouring of generosity, they often resent the volunteers for their naive, condescending, and self-important pretentions. Distributing the goods—many of them unusable or unneeded—exacerbates local congestion and slows recovery operations. Weeks and months afterwards, when victims need public support for the more prosaic tasks of replanning and rebuilding, media coverage and public concern have already declined.

America's limited recent experience provides no direct evidence of the likely psychological and social consequences and broader economic, political, and demographic effects that a truly catastrophic earthquake would have. Such an earthquake could occur in a densely populated metropolitan area that encompasses transient and normally uncohesive neighborhoods, that serves as a regional financial center, or that faces the prospect of severe aftershocks and secondary disasters, like dam failure and fires.

Economic Aspects

The primary emphasis of economic research on earthquakes has shifted over the past decade. The earliest and most heavily supported studies revolved around measuring the direct damage to residential structures and public facilities. Computer simulations of hypothetical events formed the foundation for these initial damage estimates. Depending on the assumptions made, the losses were thought to range between $3 and $60 billion for either of California's two major cities.

The perceived magnitude of damage triggered enough concern in both the National Science Foundation and the California legislature that two additional research phases were encouraged. The first broadened the investigation of damage to include (1) direct losses to midwestern and east coast cities, (2) the effects on employment stemming from damage to a region's economic infrastructure, (3) the potential for reconstruction bottlenecks emerging after a catastrophic event, and (4) a determination of who loses and who pays during the reconstruction period. The second phase focused on the economic implications of the commonly accepted means of mitigating or at least sharing losses. The major efforts undertaken included (1) measurement of the benefits and costs of building codes, (2) surveys to uncover reasons why earthquake insurance is not more widely adopted, (3) a simulation of economic dislocations resulting from a credible long-term earthquake prediction, and (4) measurement of the extent to which the creation of special study zones influences housing values. Findings from each of these areas bear on the assessment of costs and benefits for alternative engineering solutions to hazard mitigation problems.

The effects of destructive earthquakes on military installations along the west coast of the United States and on military operations should also be studied. The possible adverse effects on military operations that could result from damage to cities and industries need clarification.

Damage Estimates

The loss studies conducted during the late 1960s and early 1970s stimulated legislative initiatives and fostered a climate that produced the types of research outlined above. The staggering loss projections derived from these studies painted a broad picture. The studies were not made in depth, and little attempt was made to disaggregate effects so that differential impacts among various groups could be better understood. Nor were most of these studies designed to aid local officials in shaping land use patterns. These shortcomings are of course not a fault of the research, since the projects were not designed with these concerns in mind. However, additional efforts to refine such forecasts in either California or elsewhere are not likely to produce useful results.

Indirect Economic Dislocations

Early studies of direct damage led economists to suggest that secondary industrial and commercial dislocations might be another problem. The first attempt to model these impacts involved a crude simulation of how a regional economy might perform in the wake of a magnitude

8.3 earthquake. The model estimated the interdependence among the various economic units and forecasted unemployment and lost income. The results *suggested* that these secondary impacts might be as great as structural losses. "Suggested" is emphasized, since this and a number of succeeding studies were founded upon a theoretical model. The approach used—input-output analysis—is notorious for its lack of flexibility. It is not sensitive to price changes, new technologies, or substitutions of one ingredient in production for another. As a result, it tends to overestimate the extent to which economies respond to shocks.

Efforts have only just begun to determine the extent to which other disasters have produced such losses. A study of the worst disasters to occur in the United States over the period 1960 to 1970 reveals that no significant long-term impacts resulted. That is, the subsequent growth trend for communities sustaining losses was unrelated to the occurrence of the event. These findings proved contrary to expectations and provoked considerable debate within the disaster research community. The simplified conclusion that no significant secondary impacts result from natural disasters is not yet tenable because of several limitations in the research: (1) no major earthquakes were included in the disaster sample; (2) the average amount of destruction was small, 3.5 homes per event; (3) the impacts might have been short term; (4) the spatial unit of analysis was arbitrary. Subsequent research into the question of secondary dislocations using data gathered from earthquakes worldwide has demonstrated a strong case for sizable losses—as much as a 12 percent reduction in gross product given a $20 per capita direct loss. However, the data also suggest that a disaster-induced recession is not likely to extend beyond two years.

Because they share the same faults as damage estimate studies, regional economic models have only a limited potential. No doubt the early model studies served their purpose by alerting policy makers to the possibility that a region's economic ties might unravel in the event of an earthquake, or even the prediction of an earthquake. The need to forecast specific impacts is clearly apparent; however, the likelihood of doing so with precision is not high.

Postearthquake Reconstruction Bottlenecks

The meager amount of economic research on this subject suggests that labor and material shortages could contribute an additional 30 to 40 percent to rebuilding costs. This conclusion applies only to the most devastating events; no significant bottlenecks are anticipated for moderate earthquakes like the 1971 San Fernando quake.

Solvency of Financial Institutions in the Wake of Earthquakes or Predictions

Preliminary surveys of bank executives suggest that the policies of financial institutions vary widely depending on location, experience, geographic spread of real assets, and so on. A frequent lack of concern for solvency in the wake of an earthquake may be attributed to either the more pressing problems of the day, such as deteriorating loan portfolios, or to the extent to which holdings are diversified. Such lack of concern may also stem from the fact that an earthquake is likely to destroy only a small proportion of single-family structures. In San Fernando, for example, less than 6 percent of the homes affected were designated a ''total loss.''

Recent experience with a volatile mortgage market has demonstrated the resiliency of the country's financial institutions to a sudden erosion in the value of their assets. The soaring cost of maintaining deposits has already inflicted greater losses on the nation's lending sector than a 1906-variety earthquake in either of California's major cities probably would. This is not to suggest that the transition is or would be painless. Moreover, the focus of attention on the financial sector as a whole can divert attention from the potential problems of many individual institutions to stay solvent.

Who Loses and Who Pays for Reconstruction

Evidence on the question of who loses comes primarily from simulation studies and from an analysis of disaster loan files of the Small Business Administration. As anticipated, the share of the loss shouldered by the victim depends on the relief policy in effect. According to estimates, the liberal loan provisions offered victims of the San Fernando earthquake resulted in the general taxpayer bearing the greatest percentage of the loss. Since then the extent to which loans have been subsidized has varied considerably. However, at this point the homeowner would have to bear the greatest burden. More detailed information regarding those who lose has yet to be assembled, though some relevant work is now under way.

The Economic Efficiency of Building Codes

Building codes represent a prime application of engineering knowledge. They are implemented for reasons of health and safety, but their adoption also has economic overtones. The literature has only treated tangentially the question of how their influence on damage stacks up against the cost of implementation. Too few systematic attempts have been made to assemble costs for either new or older structures.

Because of this lack of information, policy makers have been forced to rely on rules of thumb that may prove under closer scrutiny to be economically unsound.

Earthquake Insurance

More economic research has addressed the option of purchasing insurance than any other adjustment available to the homeowner. Less attention has been devoted to the use of insurance by business establishments. The findings suggest that the low level of interest among residents of earthquake-prone areas stems from both a lack of information regarding eligibility and the negligible probability attached to a devastating event. No research has yet investigated the supply side of the problem, that is, the marketing and sales of policies. Nor has any funding been made available to investigate the role that insurance could play in the event of a credible earthquake prediction. One could speculate that demand would rise dramatically at just the time when companies curtail sales. Given the nature of risk faced by homeowners, a capability to predict earthquakes could dramatically affect insurance.

The proper role of earthquake insurance in protecting a homeowner economically is not yet clear. Insurance companies differ on the desirability of writing earthquake insurance on homes in highly seismic regions, and homeowners read conflicting statements in the newspapers about the course they should follow. The laws that govern insurance companies seem to work against a logical system of earthquake insurance for homes, and this affects the rates for homeowners. The insurance problem should be studied from an overall point of view, and correct information should be communicated to the public.

Housing Values and Special Study Zones

The creation of special study zones to shape land use planning in California has alarmed both developers and real estate interests. Surveys of the extent to which such designations have influenced actual market prices should allay these fears. Currently available evidence indicates that the price of a single-family home is unaffected by its location in a special study zone.

Governmental and Legal Aspects

Planning and preparation for destructive earthquakes requires a coordinated effort among federal, state, county, and city governments. To date, such coordination has not been achieved and local efforts are not progressing as they should. Coordination is a complex problem, because the correct planning and preparation depend on many elements. For example, a community that expects to be strongly shaken within 20 years should plan and prepare differently than a community that expects a strong earthquake within 200 years. Also, a small town faces a different problem than a large metropolitan area faces. Many different items must be considered in preparing for an earthquake, including the survival and functioning of lifeline systems, communications systems, transportation systems, fire and police departments, hospitals, social services, and other systems. At present, it is not known how much effort is justified for cities.

Research on the politics of seismic safety and the implementation of public policy has focused primarily on California, although some attention has also been directed toward Alaska, Washington, Utah, Tennessee, and Missouri. Work is just beginning in other states. The emphasis on California is quite understandable, because the state and its political subdivisions have enacted several pieces of legislation and have responded to damaging earthquakes for many years.

Seismic Safety as a Political Issue

Problems of public policy related to earthquakes are not important or persistent items on the political agendas of state or local governments. Research in California, Washington, Missouri, and a score of other states has made it clear that seismic safety is not an important issue to public officials. Likewise, officials report that their constituents do not express any significant interest in this area. Seismic safety has not been an issue of importance in state or local elections. Public opinion surveys conducted in California reveal a concern about earthquakes and show that a large percentage of the public wants strong governmental action to mitigate earthquake risk. For the most part, however, these attitudes remain private and have not led to concerted public expression, let alone to organized political activity.

In Japan and the People's Republic of China, by contrast, the earthquake problem is a matter of national policy, with leadership and resources from a centralized source. To what extent the experience in a centralized society like Japan can be applied in a decentralized country like the United States has not been adequately explored.

Seismic safety is an episodic political issue. Controversy erupts over a specific proposal, and groups and individuals try to influence official action on the proposal. When these private forces attempt to influence public policy on matters of seismic safety through political activity, their efforts almost invariably aim at stopping a proposal because those directly affected view it as unfair, unnecessary, or too costly. Very little organized political influence in favor of a proposed seismic safety policy is typically seen. Only during the months immediately following a damaging earthquake do professional groups such as structural engineers, geologists, and architects usually make a considerable and successful effort on behalf of new legislation.

Decision making about seismic safety policy is incremental rather than comprehensive. The lack of any clearly stated and implemented policy on what risk from earthquakes is acceptable illustrates this fact. Rather than making the comprehensive evaluations and decisions required for a policy of acceptable risk, public decision makers consider seismic safety on a case-by-case basis when the subject periodically arises.

Land Use Planning

California has been a pioneer, through two state laws, in the attempt to use land use planning for purposes of seismic safety. All local governments in California are required to prepare a general plan, and since the 1971 San Fernando earthquake each of these plans has had to contain a Seismic Safety Element (SSE) for local governments to use in land use planning. Another aftermath of the 1971 earthquake was a state law requiring the State Geologist to designate areas of approximately one eighth of a mile on either side of known active faults as special studies zones. Within these zones, no structure may be built astride the fault, and a geologic report must accompany any proposed development, other than those consisting of three or fewer single-family homes. Furthermore, sellers of homes within the zone must disclose to prospective buyers that the property is located within a special studies zone.

Virtually all of the general plans of local governments in California now have the mandated Seismic Safety Element. Not unexpectedly, they vary in quality. Most contain recommendations for further refinement of geologic data, as well as specific regulatory actions for the jurisdiction to undertake as part of land use planning. But local governments have implemented very few of the specific recommendations and regulatory actions adopted as official policy in the SSEs. Instead, the SSEs seem to have served the somewhat amorphous function of having increased the awareness of developers, real estate agents, and public officials involved in land use decisions to earthquake risk. The SSEs have brought elements of high risk to the attention of city officials and have eliminated some of the more blatant violations of good land use policy for seismic safety, but they do not play a prominent role in land use decisions.

The Special Studies Zone Act has had the obvious effect of prohibiting new structures across or very near known active faults. Many projects throughout California have been carefully designed to avoid placing lifelines or structures in locations subject to surface rupture. Controversy over implementing the act has arisen over the precise location of faults and whether high-rise buildings (e.g., hotels) or critical facilities (e.g., hospitals) should be allowed within a zone. New critical facilities and new high-rise buildings have usually been denied, but additions or renovations to existing structures have usually been permitted. The part of the law requiring disclosure does not seem to have affected the exchange of real property within special studies zones.

After an earthquake, redesignations of land use may prevent a repetition of damage and loss of life due to improper or technologically obsolete land use practices. A careful examination of patterns of land use after earthquakes in Anchorage, Santa Rosa, and San Fernando produced a few important conclusions: (1) major changes in preearthquake land use patterns or norms and practices are unlikely; (2) aid from the federal government can significantly affect the decisions of local governments with respect to land use after an earthquake, especially for public facilities; (3) not all decision making after an earthquake takes place quickly in an atmosphere of crisis—some communities give deliberate attention to postearthquake planning; (4) any postearthquake changes in land use require the presence of motivated and persistent local officials who are willing to resist the inevitable pressures simply to return to preearthquake patterns of land use.

Building Codes

Most local governments in areas of moderate to serious seismic risk have adopted building codes that represent current engineering thought about the earthquake resistance of ordinary structures. Serious questions surround the actual implementation of the codes, however. Many local governments, for example, do not have civil or structural engineers on staff, thus making plan checking and on-site inspection of engineered buildings questionable in some cases. Not much is known about how well seismic codes are enforced.

Only a handful of communities have undertaken programs to reduce the vulnerability of buildings constructed prior to the adoption of modern building codes. This is true even in California, despite the almost universal commitment by local governments to remedying the problem of old buildings. The overwhelming majority of SSEs in California have made reducing or eliminating this problem an accepted policy. The cities of Long Beach and Santa Rosa, for example, have slowly been rectifying the problem over the last decade. Los Angeles just embarked on a 15-year program to require the rehabilitation of approximately 8,000 old buildings, but serious questions about financing remain. Most local jurisdictions have refused to fund the inspections and investigations needed to locate old buildings that are structurally suspect. City officials and representatives of the development industry in St. Louis successfully rebuffed an effort by the Department of Housing and Urban Development to upgrade seismically related building standards in that city. In California and St. Louis the governmental decision makers remain unconvinced that the cost and inconvenience necessary to deal with old buildings effectively are worth the economic dislocations and political retributions likely to ensue. Some economists would agree.

Emergency Response Planning

Planning a response prior to an earthquake remains a very low priority activity with most of the public organizations that respond to emer-

To assist governmental agencies in responding to earthquake emergencies, a number of agencies have created emergency operations centers. These centers can be either at the state, county, or city level. This photograph shows the operation of the Los Angeles City Emergency Operations Center during the October 2, 1980, "Shaker I" earthquake exercise. At this location are representatives of all public service emergency facilities (fire, police, and hospital) and essential facilities (water, energy, transportation, and communications). The center performs an essential service in coordinating the recovery operation after an earthquake. Photograph courtesy the Los Angeles Police Department.

gencies. Not only are formal plans frequently skimpy and sometimes obsolete, but actual practice through training sessions and simulations is sporadic at best. One of the most serious problems in previous earthquakes, particularly in metropolitan areas, has been the difficulty in communicating and coordinating the activities of neighboring jurisdictions. This problem remains in most metropolitan areas.

Several notable exceptions to the above generalizations occur in the city and the county of Los Angeles. In general, however, most governments have given only scant attention to emergency response planning for earthquakes. They have assumed that their "normal" emergency response procedures will be able to handle the devastation of an earthquake.

Legal Aspects

Governments may have significant problems of liability after a damaging earthquake if they fail to take reasonable precautions with public property and if they fail to regulate the private sector in a reasonable fashion. American research on the legal aspects of earthquake prediction and hazard mitigation has focused on determining the current state of the law concerning land use, regulation of building construction, government liability, and disaster relief. Further research to clarify legal responsibility and liability should help to overcome a frequent obstacle to decisive public action toward implementing contributions from engineering to mitigate earthquake hazards.

Differential Impact and Response

The impact of earthquakes, earthquake preparedness, and earthquake reconstruction is different for different segments of the population, such as ethnic and racial minorities, socioeconomic classes, age groups, and inhabitants of different regions. This calls for different solutions to problems of hazard mitigation. Contributing to this differential impact are differences among individuals and population segments in (1) *vulnerability*, (2) *access* to communication and to public authorities, (3) *experience* with disasters and in dealing with authorities, (4) *resources and skills* for dealing with the trauma and loss of an earthquake, (5) *culture* that establishes value priorities and gives events distinctive meanings, and (6) *self-interest* based on the group's relationship to the larger community. The following paragraphs consider these differences in turn.

1. Common examples of exceptional vulnerability include living and working in seismically hazardous buildings, in mountainous regions with narrow roads, downstream from seismically substandard dams,

or in low-lying coastal zones. In portions of the eastern and midwestern United States where unreinforced masonry is favored in home construction, poor people may be less vulnerable, in their cheaper wood frame houses, than are the wealthy. But in California, where building codes have long included seismic elements, disadvantaged minorities, the poor, and the aged disproportionately use structures built before strict codes were adopted. These structures provide low-cost housing and low-cost commercial space, and rents will certainly increase if the owner spends money to upgrade his structure. In some cases, such as in apartment buildings occupied entirely by the elderly, the tenants said that they preferred taking the earthquake risk rather than being displaced and paying increased rents. There is always a danger that legislation designed to discourage construction in especially hazardous locations, such as active fault zones, may have the unintended effect of increasing the concentration of the poor and elderly in these areas.

2. Research in southern California indicates that older adults are better informed but less well prepared than younger adults on earthquake matters. Blacks and Mexican-Americans are less likely than whites to be well informed. Ethnic and racial minorities are often culturally and economically cut off from official communications, and so are inclined to disregard them unless their own leadership endorses the official notices. Californians are generally better informed about earthquakes and earthquake safety than are residents in other earthquake-prone regions of the United States.

3. Recent migrants and tourists in earthquake-prone regions, to whom an earthquake is a disorienting experience, are also most likely to be overlooked by authorities and not to receive or comprehend emergency messages.

4. Regions marked by economic backwardness and widespread poverty lack the resources needed for earthquake preparedness, emergency response, and postearthquake reconstruction. Thriving urban communities have more resources, but the concentrated population augments vulnerability, and some credible scenarios depict a level of casualties and destruction that could strain or exhaust local and national resources in the United States. The poor, the elderly, and the handicapped depend more on public assistance in preparing for an earthquake. As victims they also depend more on bureaucratic mazes to secure emergency aid for relocation and reconstruction yet are less able to navigate those mazes. Their needs for postdisaster housing and employment are often overlooked in reconstruction planning, especially in Third World nations. Least able to help in their own rescue following an earthquake are institutionalized populations, such as hospital patients and prisoners.

5. Differences among Mexican-American, black, and white cultures

are reflected in especially high rates of fatalism about earthquakes among blacks, who tend to be skeptical about scientific and technological advances in earthquake prediction and earthquake engineering. Mexican-Americans, on the other hand, are more optimistic and exhibit more faith in authorities. Severe miscalculations and misunderstandings result when those who develop hazard mitigation plans do not understand and take into account cultural differences of this sort.

6. Differences in self-interest are least often recognized. Because of the long intervals between damaging earthquakes, the potentially long lead time for predictions, and the relationship of these time intervals to their remaining life spans, many elderly people, not surprisingly, are unwilling to undergo the disruptions involved in escaping from or correcting a seismically unsafe situation. Even during the period of emergency, when such compounding disasters as aftershocks, dam failure, and tsunamis may threaten, emotional attachment to their homes often makes the elderly reluctant to evacuate. Underprivileged minorities, who are often compelled by hazard mitigation programs to move great distances from their workplaces and pay impossibly large fractions of their limited incomes for new housing, may understandably prefer to accept the risk of remaining in a seismically unsafe building in a familiar neighborhood.

Conclusion

The implications for engineering research of this brief sampling of research into the social, economic, and political aspects of earthquakes can be summarized in five general observations. First, many of the crucial problems in earthquake safety today have less to do with technology than with implementation, because there are many economic, political, social, and psychological impediments to the use of that technology. Engineering knowledge has surpassed the corresponding social and economic understanding.

Second, the choice among alternative engineering approaches to problems of earthquake hazard mitigation depends on some estimate of potential benefits versus costs. The direct and indirect benefits and costs of any engineering solution always include social, psychological, economic, and political components. Only by better understanding these components and by using the available understanding more fully can optimal decisions be made about the development and application of earthquake technology.

Third, although social and economic research directly concerned with earthquakes is in its infancy, there is a rich body of applicable understandings from the behavioral, social, and economic sciences that personnel who develop and apply technology in earthquake hazard mitigation do not use fully.

Fourth, social and economic research has much to contribute to the long-term enhancement of seismic safety, but it seldom generates so immediately concrete and practical a product as a new invention might. Social and economic research helps earthquake safety planning most when used as basic understanding rather than as simple formulas that can be mechnically applied.

Finally, the design and use of technology must reflect a sensitive awareness that the solution to the earthquake problems of one community or segment of the population may exacerbate the problems of another community or population segment.

10

Earthquake Engineering Education

Implementing an effective earthquake hazard mitigation program requires the generation of basic knowledge on the nature of the threat and on how to minimize its negative impact. In addition, effectively applying the knowledge requires a body of educated earthquake engineers. Over the past decade research in the fields of engineering seismology and earthquake engineering has made much progress in generating needed knowledge and in applying it in engineering practice. The major accomplishments during this period and those areas where future research is needed have occupied the previous chapters of this report.

Unfortunately, a considerable time lag exists between the generation of new knowledge and its effective application through design codes. This time lag, which typically amounts to approximately 10 years, is influenced by many factors. However, it comes primarily from communication problems in reporting, transferring, and comprehending such knowledge and from difficulties in molding such knowledge into practical forms. Obviously, education plays a key role not only in generating new knowledge but in effectively applying it to engineering practice.

This chapter describes the methods and trends that have developed in earthquake engineering education over the past decade in the United States, evaluating their overall effectiveness, pointing out certain deficiencies that currently exist, and making recommendations as to educational needs for the future.

Academic Programs

Research in earthquake engineering over the past decade has greatly augmented the ability to analyze and design structures that will perform satisfactorily under expected seismic conditions. A basic component in implementing this capability into the engineering and architectural professions has been the modernization of academic programs in colleges and universities.

Because of the advanced nature and complexity of modern methods of analysis and design, the curriculum at the undergraduate level has understandably not changed profoundly. However, basic courses in mechanics now place greater emphasis on the theory of dynamics, and courses in soil mechanics and structures give more attention to the effects of vibrations and dynamic forces, including those produced by earthquakes. This is probably a response to a greater interest in earthquake engineering and to an increased awareness of the needs students have who will go on in this field. Engineering graduates entering professional employment at the bachelor's level are therefore more cognizant of the earthquake problem and better equipped to grapple with it than were their counterparts a decade earlier.

Changes in the curriculum at the graduate level have been much more pronounced. Typically, specialized courses in structural dynamics, foundation dynamics, and seismic design make their first appearance at the graduate level, although some are also available to advanced undergraduates as elective courses. Master's level programs in structural and geotechnical engineering, and occasionally in hydraulic engineering, regularly include these courses.

More civil engineering students, representing a larger fraction of the baccalaureate pool, are continuing their education to the master's level, which reflects the increasing complexity of modern industrialized society. Graduates at this level often play a leading role in applying new earthquake engineering developments to the design of earthquake-resistant structures. Thus they are a principal ingredient in the development of professional practice in earthquake engineering.

The number of students with specialization in structural dynamics and/or earthquake engineering who continue to the doctorate level has increased over the past decade. There are three reasons for this increase: (1) the availability of research support, (2) the need for greater knowledge, and (3) the increased demand for graduates at this level in universities, government, and industry. Currently, an estimated 10 to 15 students graduate at this level each year in the United States, of which somewhat more than half are foreign students, many of whom return to their home countries. This number of graduates does not meet the total demand, for universities, research laboratories, and industry have a greater need than can be supplied.

This undesirable situation will undoubtedly become much worse in the future unless effective steps are taken to prevent it. Numerous trends support this prediction: (1) technological advances continue to escalate the demand in industry, (2) rapidly increasing numbers of faculty retirements over the next decade will sharply increase the demand in universities, (3) significantly higher starting salaries offered by industry as compared with those offered by universities will cause severe difficulties in recruiting new faculty members, (4) increasing educational costs will make it more and more difficult for students to complete doctoral programs, (5) increasing pressures to reduce budgets threaten research support essential to doctoral programs, and (6) demographic data indicate that the total pool of eligible U.S. students for doctoral programs will diminish substantially in the next decade. Although the number of doctoral students in civil engineering increased considerably during the 1970s, statistics indicate that it has passed its peak and is now diminishing. Also, the number of U.S. students as compared with foreign students is dropping.

The shortage of engineers with postgraduate education poses a serious problem, not only in earthquake engineering but also in most other branches of engineering. The shortage would be even greater were it not for the large numbers of foreign engineers now working in the United States. Many of these are from Asia and the Middle East, and the practice of engineering now relies heavily upon their services.

Education in earthquake engineering should have a strong measure of laboratory work. This should include such things as generating structural vibrations; measuring and recording structural accelerations, velocities, and displacements; measuring and recording ground shaking; and testing materials, structural elements, and model structures under conditions similar to those experienced during earthquakes. Universities are, in general, not well equipped for such laboratory work, primarily because of the required expense.

Changes in curricula to introduce seismic considerations into architectural design and planning have been minimal in the programs for professional degrees at schools of architecture. A recent survey of more than 100 programs at schools that teach hazard design to architecture students, to which fewer than one third responded, indicates that a significant percentage of the programs offer no course work in the nonstructural (architectural) design issues of seismic safety. This is particularly disturbing in light of the assumption that the small percentage that responded could be the most interested group. The survey also observed that there appear to be two separate faculties in schools of architecture, one teaching support courses and one teaching design, but the two do not appear to communicate or share significantly with each other. In view of the importance of seismic safety issues in the architecture profession, measures are needed to improve the support of this activity in educational programs.

Publications

New knowledge generated in any field needs to be fully documented and widely distributed in the open literature before it can be useful to society. In earthquake engineering such knowledge is normally first published as technical reports of individual research projects, postearthquake investigations, and technical papers in journals and conference proceedings. The number of such publications grew sharply in the United States during the last decade, and they cover a wide variety of topics, mainly in the broad fields of engineering seismology; strong-motion seismometry; the dynamics of rocks, soils, foundations, and structures; earthquake-resistant design and construction; hazard assessment and reduction; and earthquake effects.

While the large number of earthquake engineering publications of the past decade served well to record the new knowledge generated, time permits the individual engineer to study only a very small percentage of them. Thus a great need exists to screen, consolidate, and remold the new knowledge so as to speed up its effective use in seismic design and construction practice. To meet this need, the preparation of monographs, state-of-the-art papers and reports, and code commentaries should be encouraged and supported financially. Furthermore, the preparation of text and reference books on various topics in earthquake engineering should be encouraged.

Continuing Education

Many engineers who are responsible for the design of earthquake-resistant structures have a limited educational background in such subjects as earthquake engineering, structural dynamics, and computer-oriented computational methods, even though they must use these disciplines more and more in their work. A fifth year of study leading to a master's degree normally covers these subjects, but many engineers in practice have not taken such courses because they chose to enter the profession at the bachelor's level. The shortage of engineers and the resulting high salaries at this level encourage this trend. It is therefore essential that an effective continuing education program be developed to provide an opportunity for the practicing engineer to receive the education needed in the specialized disciplines of earthquake engineering.

Traditionally, these programs have consisted of concentrated short courses lasting for five days, usually during the summer. Some of these programs have been held annually and have emphasized fundamental concepts; others have been held periodically and have emphasized research developments. Both types are important, but the question arises as to how much material participants can grasp and retain with such a short, concentrated exposure. Recent programs have extended courses over many weeks, with a limited number of lectures presented each week, as in a regular university course. While these extended courses help avoid the problem of concentration, they limit attendance to the local constituency. In some cases, lectures have been recorded on closed-circuit television, allowing in-house participation.

A major problem facing all continuing education courses is the high cost of operation. Typical rates for the concentrated short courses have reached $150.00 per day, and they will continue to rise yearly. This cost, coupled with time away from the office, makes it difficult for practicing engineers to justify such an expense unless they work for large organizations.

Effective measures to improve continuing education should be implemented. A fellowship program is needed that would allow engineers to return to universities full time for one or more academic terms. This would give engineers an opportunity to upgrade their knowledge in earthquake engineering while relieving them of some of the financial burden. In some cases, academic policies would have to be changed so that fellowship recipients could take regular university courses without being in a degree program.

Other possible programs should be considered, including a program whereby practicing engineers would join university staffs for one or more academic terms in exchange for faculty members joining their firms for the same period. This would allow the practicing engineers to upgrade their analytical background by auditing courses while teaching the more practical design courses. On the other hand, faculty members would strengthen their practical experience, making them more effective teachers upon their return to the university. Also, expanded and more effective use of closed-circuit television should be considered for industrial in-house presentation.

Specialized Seminars and Workshops

Seminars and workshops on specialized topics have in recent years effectively educated architects, engineers, and planners in various aspects of seismic safety. Brief descriptions of some of these activities follow.

An extensive workshop entitled "Building Practices for Disaster Mitigation" was held in Boulder, Colorado, in 1972 under the sponsorship of the National Science Foundation (NSF) and the National Bureau of Standards. It provided an initial focus on many issues of research and practice in earthquake engineering.

In 1976 the Earthquake Engineering Research Institute (EERI) and the Structural Engineers Association of California (SEAOC) organized a series of eight lectures in San Francisco and Los Angeles under the title "Interpreting Strong Motion Records for Earthquake Design Criteria and Structural Response." Because of the success of this series, EERI organized its "Regional Seminars on Earthquake Design Criteria, Structural Performance, and Strong Motion Records," which were given in 1979 in Mayaguez, Puerto Rico, St. Louis, Houston, Washington, D.C., Seattle, and Chicago under the sponsorship of NSF. In 1982 EERI gave this seminar series in Raleigh, North Carolina, Salt Lake City, Utah, and Anchorage, Alaska. EERI plans to continue this seminar series in other cities of the United States. It has also organized one-day seminars on timely specialized topics in earthquake engineering, which in recent years have immediately preceded the annual business meetings.

The Applied Technology Council (ATC) has also made major contributions to education in earthquake engineering. ATC, an independent, nonprofit, tax-exempt corporation, was established in 1971 through the efforts of SEAOC. It was charged with introducing technological developments into active practice in structural engineering, so that applied research performed by university groups and others would greater benefit the general public. Seminars and workshops held by ATC include those documented in the publications *Building Practices for Disaster Mitigation* (ATC-1), *Proceedings of a Workshop on Earthquake Resistance of Highway Bridges* (ATC-6-1), *Guidelines for the Design of Horizontal Wood Diaphragms*, and *Design of Prefabricated Concrete Buildings for Earthquake Loads*. The National Science Foundation, the National Bureau of Standards, the Department of Housing and Urban Development, and the Federal Highway Administration provided funds for these activities.

The northern and southern sections of SEAOC usually hold one or two technical seminars each year on timely topics, such as seismic analysis by computer, code developments, or damage mitigation of unreinforced masonry structures built prior to 1933. These seminars are well attended by practicing engineers.

In 1977 and 1978 the American Institute of Architects (AIA) Research Corporation, under the sponsorship of NSF, held seminars at Stanford University and the University of Illinois to present and discuss seismic issues in architecture as they relate to professional procedures and educational programs. Similar presentations and discussions were included in seismic workshops at the 1979 and 1980 AIA national conventions. These workshops focused mainly on the issues presented in the book *Architects and Earthquakes*, which was prepared by the AIA Research Corporation with funds provided by NSF.

Since 1978 USGS and the Federal Emergency Management Agency (FEMA) have sponsored conferences and workshops on such topics as "Communication of Earthquake Prediction Information," "Preparing for and Responding to a Damaging Earthquake in the Eastern United States," and "Continuing Actions to Reduce Earthquake Losses in the Mississippi Valley Area." USGS has sponsored a dozen conferences on technical aspects of earthquake prediction. FEMA, with funding from NSF, USGS, and DOE, has also organized seminar-type courses in the general area of hazard design for architects and engineers. These courses were presented in Emmitsburg, Maryland, in 1981, and FEMA proposes to hold them annually in Emmitsburg as funds are available. These courses are an expansion of a series offered in earlier years in Battle Creek, Michigan.

Seminars and workshops of the type described above fill a definite need in the formulation and transfer of information on specialized topics associated with seismic safety. Carefully planned and timely activities of this type should therefore continue in the future.

Conferences

Research conferences provide opportunities for research workers to learn what their peers are doing and discuss special research topics. Such conferences make important contributions to the advance of knowledge. In addition, the oral presentations of papers at technical conferences usually initiate professional awareness of new knowledge from research programs in earthquake engineering. The learning process of the engineer or architect then continues by means of selected published papers. Following are brief descriptions of the leading conferences of interest to the earthquake engineering community.

The American Society of Civil Engineers (ASCE) sponsors technical presentations on topics in earthquake engineering as part of its regular conventions and in specialty conferences. All of these technical sessions are organized through its technical committees and technical councils, especially the Soil Dynamics Committee of the Geotechnical Division, the Dynamics Committee of the Engineering Mechanics Division, the Committee on Dynamic Forces of the Structural Division, and the Technical Council on Lifeline Earthquake Engineering.

Earthquake engineering has been a topic of increased interest in such technical meetings. The ASCE held the following meetings in 1981 and 1982 that included this topic: (1) the specialty conference "Dynamic Response of Structures: Experimentation, Observation, Prediction, and Control," Engineering Mechanics Division, Atlanta, January 1981; (2) a technical session in the spring ASCE convention, Technical Council on Lifeline Earthquake Engineering, New York, May 1981; (3) a specialty conference on lifeline earthquake engineering, Technical Council on Lifeline Earthquake Engineering, Oakland, California, August 1981; (4) a technical session on performance of water transport systems during earthquakes in the spring ASCE convention, and a technical session on optimum design in earthquake engineering, Technical Council on Lifeline Earthquake Engineering and Soil Dynamics Committee of the Geotechnical Division, Las Vegas, April 1982; (5) "23rd Structural Dynamics and Materials Conference," New Orleans, May 1982; and (6) a technical session on remedial measures to improve the dynamic stability of earth structures in the ASCE annual convention, Geotechnical Engineering Division, New Orleans, October 1982.

The American Concrete Institute (ACI) is a nonprofit, nonpartisan organization of engineers, architects, scientists, and constructors with a technical interest in the field of concrete. Its primary objective is to assist its members and the engineering profession by gathering and disseminating information about the properties and applications of concrete and reinforced concrete. Since 1905 it has achieved this objective through individuals and committees working in cooperation with public and private agencies. Various media make the work of the institute available to the engineering profession, including the *Building Code Requirements for Reinforced Concrete* (ACI 318-77), the *ACI Journal*, technical sessions at semiannual meetings, and a variety of technical publications.

During the 1970s various committees within the institute became increasingly concerned with the earthquake-resistant design of reinforced concrete structures. Those ACI committees have addressed seismic problems associated with the loading, strength, and response of structural components and building systems. Among the active committees are (1) the Committee on Standard Building Code (ACI 318), (2) the Committee for Lateral Forces on Reinforced Concrete Buildings (ACI 442), (3) the Committee on Joints and Connections in Monolithic Concrete Structures (ACI 352), (4) the Committee on Inelastic Behavior of Reinforced Concrete Structures (ACI 428), (5) the Committee on Reinforced Concrete Columns (ACI 441), and (6) the Committee on Shear and Torsion (ACI 445). At their regular semiannual meetings the committees plan ongoing activities to promulgate the findings of research on the use of reinforced concrete in seismic areas. The ACI special publications *Reinforced Concrete Structures in Seismic Zones* (SP-53) and *Reinforced Concrete Structures Subjected to Wind and Earthquake Forces* (SP-63) are examples of these activities.

The Structural Engineers Association of California sponsors two days of technical sessions at its annual convention, which results in papers on earthquake engineering. These papers are published in proceedings that all members of the association receive.

Nine international engineering and scientific societies sponsor the

Offshore Technology Conference (OTC). Since its founding in 1968 the conference has come to be recognized as the leading annual meeting on ocean research and technology. Many of the technical sessions deal with the analysis and design of offshore structures, with major consideration given to earthquake and wave forces.

The Earthquake Engineering Research Institute organized and sponsored the First U.S. National Conference on Earthquake Engineering in 1975 at the University of Michigan and the Second U.S. National Conference on Earthquake Engineering in 1979 at Stanford University. EERI also planned and sponsored the First World Conference on Earthquake Engineering at the University of California, Berkeley, in 1956 to observe the fiftieth anniversary of the 1906 San Francisco earthquake. The Second World Conference on Earthquake Engineering was held in Japan in 1960 under the sponsorship of the Science Council of Japan. The organizers of that conference fostered the creation of the International Association of Earthquake Engineering, which has since sponsored all subsequent world conferences in New Zealand (1965), Chile (1969), Italy (1973), India (1977), and Turkey (1980). The eighth world conference will be held in San Francisco in 1984, with an expected attendance of 1,500.

The Universities Council for Earthquake Engineering Research (UCEER) periodically holds conferences to generate an awareness among university researchers of ongoing research activities in earthquake engineering and to stimulate new ideas that will advance the overall research effort. These conferences have been held at the California Institute of Technology (1967), the University of California, Berkeley (1969), the University of Michigan (1974), the University of British Columbia (1976), the Massachusetts Institute of Technology (1978), and the University of Illinois (1980). All of these conferences have received financial support from NSF.

Information Service Programs

In the late 1960s it was recognized that the transfer of technology in earthquake engineering should be improved, so that research results from the rapidly expanding national effort would be implemented more rapidly. Responding to this need, the NSF funded the National Information Service in Earthquake Engineering (NISEE) in 1971 to provide technology transfer for all groups and individuals involved in seismic safety. This service has continued to the present through complementary programs at the California Institute of Technology (CIT) and the University of California, Berkeley (UCB).

The NISEE performs three basic services: (1) it transfers information from the specialized earthquake engineering libraries at CIT and UCB to the practicing professions, government agencies, academic institutions, and the general public; (2) it distributes computer programs and strong ground motion data to all interested parties; and (3) it publishes the annual *Abstract Journal in Earthquake Engineering*.

NISEE's information transfer service makes available unique collections of materials relevant to earthquake hazards and their mitigation. The Earthquake Engineering Research Center Library at UCB has to date assembled over 16,000 items, and the corresponding library at CIT has assembled a similar number. The items include research reports, technical journals, conference proceedings, monographs, slides, and maps. In addition to their major emphasis on earthquake engineering, these libraries collect materials in the related fields of engineering seismology, geology, and disaster planning. Nontechnical publications on all aspects of earthquakes are also available, and these libraries contain foreign as well as domestic literature. The number of external library transactions in the NISEE program has grown steadily over the past decade to about 10,000 per year.

Presently, the UCB-NISEE activity distributes approximately 55 different specialized computer programs in earthquake engineering. These programs have been developed by universities engaged in research and by private engineering consulting firms. Currently, about 500 programs and about 1,800 program manuals are distributed each year. Since the original recipients further distribute these items, the dissemination by NISEE of computer programs contributes greatly to technology transfer in earthquake engineering. Dissemination of strong ground motion data, primarily through the CIT-NISEE program, has had similar success. The service makes available hundreds of different digitized strong ground motion accelerograms of real earthquakes.

The *Abstract Journal in Earthquake Engineering* provides the only comprehensive annual collection of abstracts and citations of world literature in earthquake engineering. The number of subscriptions has steadily grown at about 35 percent per year since 1973 to reach the current level of 830. This journal is extremely effective in locating literature on any specialized topic in earthquake engineering.

Another major center that contributes to the transfer of information on seismic issues is the Natural Hazards Research and Applications Information Center at the University of Colorado in Boulder. Funded by the Federal Emergency Management Agency, the National Oceanic and Atmospheric Administration, the U.S. Geological Survey, and the Corps of Engineers acting through NSF, the center seeks to strengthen communication between research workers and the individuals, organizations, and agencies concerned with public action relating to natural hazards.

Because the information centers described above play a major role in transferring basic knowledge to the professional groups that implement that knowledge, it is imperative that they continue to be funded so as to provide at least the current levels of service.

Impact of Earthquake Engineering Education on Seismic Safety

The success of any reseach program must ultimately be judged in terms of its impact upon society. Thus the earthquake engineering program must be evaluated in terms of the impact its improvements in engineering practice and construction have had on seismic safety. As pointed out earlier, earthquake engineering education, in the broad context of publications, academic programs, continuing education courses, specialized seminars and workshops, conferences, information service programs, and seismic codes, regulations, and commentaries, plays a major role in the successful implementation of research results. While the earthquake engineering research program and its associated educational programs have clearly been successful, further research is needed in specialized areas, as outlined in earlier chapters of this report. Also, the educational implementing process needs further strengthening to ensure that research results are used effectively. To optimize this overall effort, all of the participating professional groups (researchers, educators, planners, architects, engineers, and government officials) need to interact and cooperate. Also needed are greater public awareness and acceptance of needed programs.

Recommendations

To meet further demands on earthquake engineering education, actions should be taken along the following lines:

1. The number of U.S. Ph.D. students should be increased through incentive programs so as to meet the growing demand in industry, universities, and government for their services.
2. Earthquake engineering laboratories at universities should be supplied with modern instruments and equipment, and appropriate experimental courses should be developed.
3. Programs for academic degrees in architecture and engineering should be continually upgraded to keep pace with new developments in earthquake engineering and the changing needs of the practicing professions.

4. Improved financial support for qualified American students should be provided so that more of them will continue their engineering education beyond the bachelor's level.

5. The differential between academic and industrial salaries, particularly at entry levels, should be eliminated so that universities can compete in attracting and keeping brilliant young Ph.D. graduates.

6. Current and new knowledge generated through earthquake engineering research should be screened, consolidated, and remolded into written forms more suitable for implementation—namely, monographs, state-of-the-art papers and reports, code commentaries, and text and reference books.

7. Improved opportunities should be provided for engineers employed in industry to return to universities for advanced degrees or continuing education in earthquake engineering.

8. Programs should be developed whereby engineering faculty members join industrial firms for limited periods to gain practical experience while practicing engineers join academic groups to work in research and/or teaching for similar periods and strengthen their analytical background.

9. Seminars and workshops should be held on timely new developments in earthquake engineering.

10. Specialized national and international conferences on earthquake engineering and on earthquake engineering research should be held periodically to expose all interested groups to new developments.

11. National information service programs should be maintained at present or greater levels of effort.

12. Seismic code provisions and regulations used by architects and engineers should be continually upgraded to keep pace with new knowledge and developments generated through research programs.

13. Appropriate steps should be taken, through TV programming or otherwise, to create a greater awareness and understanding by the general public and public officials of the causes, consequences, and mitigation of all natural hazards, including earthquakes.

The above actions must be carefully planned, through a coordinated effort by architects and engineers at all levels and managers in universities, government, and industries, and be adequately funded to be effective.

11

Research in Japan

Destructive earthquakes affect many countries, making earthquake engineering research an international concern. The First World Conference on Earthquake Engineering was held in California in 1956, with participants from 10 countries. Since then world conferences have been held at four-year intervals in Japan, New Zealand, Chile, Italy, India, and Turkey. At the seventh world conference in Turkey, 750 participants from 42 countries reported on their earthquake problems and research.

Two large industrialized countries with important earthquake problems are the United States and Japan. Both have conducted programs of earthquake engineering research during the last decade, so a comparison between them can be informative. Japan, with a population of 112 million, has a land area approximately one tenth that of the United States and has somewhat greater seismic activity. Therefore the probability that a large earthquake will occur close to a populous city is greater for Japan than for the United States, and in this sense Japan has a worse earthquake problem than does the United States. Both countries have suffered a great earthquake disaster in this century—the San Francisco earthquake of 1906 in the United States and the Tokyo earthquake of 1923 in Japan. Both countries are also now anticipating a great earthquake in the not-too-distant future. In Japan there is concern about a repetition of the 1923 disaster, and in the United States there is concern about a repetition of the 1857 Fort Tejon earthquake, with a magnitude of 8.3, on the San Andreas fault adjacent to Los Angeles.

In January 1982 four U.S. earthquake engineering researchers, who had interacted with the Japanese earthquake engineering community previously, visited major Japanese earthquake organizations in Japan. The purpose of the visit was to obtain the most recent data on Japanese activities and funding and to verify previously obtained information. The team had a cordial reception and was given all the requested data that could be assembled. As it gathered this data, the team realized that although there are many similarities between the Japanese and U.S. earthquake research communities, there are also striking differences. Without judging which approaches are better, a review and

This building in Tokyo collapsed during the 1923 earthquake. Some 100,000 people lost their lives during this earthquake. It led to the establishment of the Earthquake Research Institute at Tokyo University.

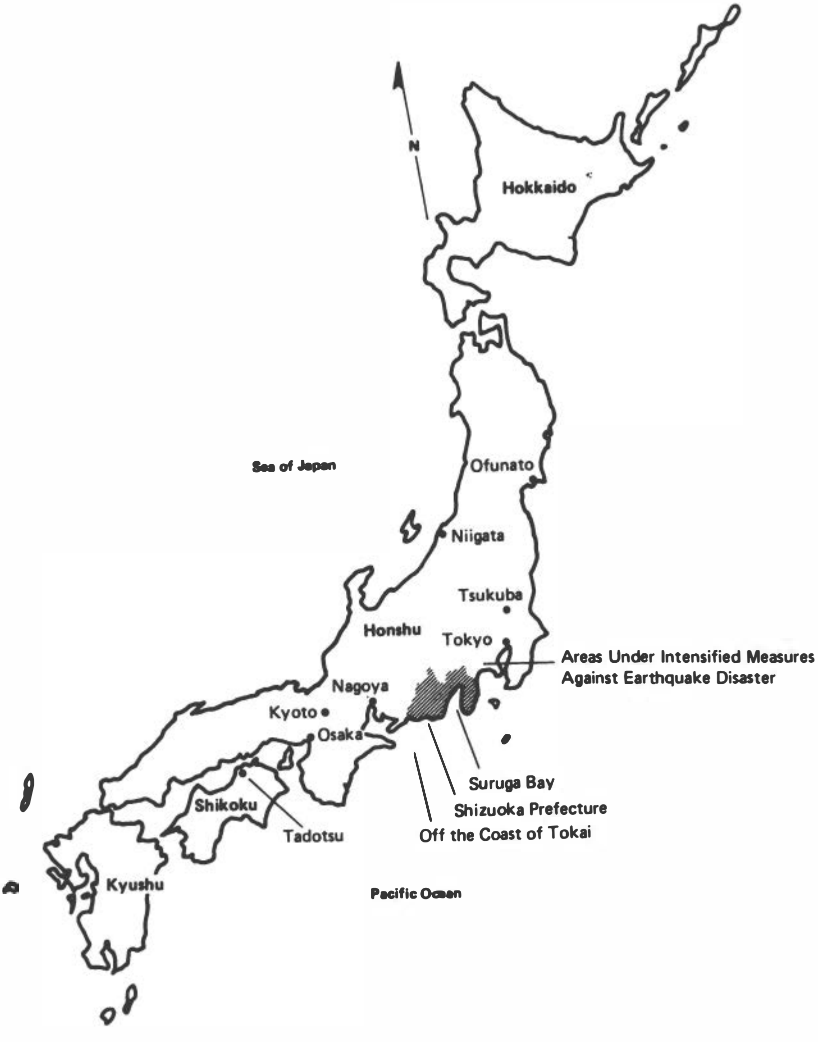
evaluation of certain aspects of the Japanese approach could point toward their possible use in the United States.

Many different government agencies, universities, and industries are involved in various aspects of earthquake engineering research in Japan. For instance, many government agencies actively do research and carry out earthquake preparedness programs.

The different organizations seem to cooperate considerably, even though the research groups share a friendly and beneficial competition. This chapter summarizes current research and implementation activities, discusses several major new experimental research facilities, and estimates the Japanese financial commitment to earthquake hazard mitigation.

Overview

Japan has a total land area of 377,728 km², distributed mainly among four islands. Its population of 112 million is mostly concentrated in large cities along the coast. Most of the country (80 percent) is mountainous and is geologically hazardous for construction because of active faults, volcanic regions, and areas of large potential landslides. Because the Japanese Islands are situated on the circum-Pacific earthquake belt, frequent major earthquakes have resulted in the loss



Map of Japan.

of lives and property. Therefore, Japan's mitigation program for seismic hazards is among the most demanding in the world.

During its history Japan has suffered many earthquake disasters. Many consider the Nobi earthquake of 1891 the starting point for earthquake engineering and seismological research in Japan. In 1923 a large earthquake and fire destroyed most of the buildings in the capital city of Tokyo, causing about 100,000 deaths.

The seismicity of Japan differs from that of the United States in that most of Japan's very large earthquakes originate offshore of the Pacific coast on a major subduction fault zone. In the United States large earthquakes occur on the San Andreas strike-slip fault zone, on associated faults, and in other inland regions such as Nevada, Washington, Missouri, and South Carolina. Approximately three times as many people live in the highly seismic regions of Japan as in highly seismic regions of the United States. Since 1932, earthquakes in Japan have killed 16,200 people and have destroyed 110,000 housing units. These housing units cannot be compared directly with housing units in the United States, though modern commercial and industrial buildings are comparable with those in the United States.

In Japan, government agencies, universities, industrial laboratories, and research associations each study a number of different facets of the earthquake problem. Although many groups work on various parts of the same problem, a designated agency or ministry is responsible for coordinating all governmental efforts. The following sections illustrate this functioning.

Earthquake Warning

Efforts to predict earthquakes in Japan are coordinated by the Science and Technology Agency (STA) (roughly akin to the U.S. Office of Science and Technology Policy but with a larger budgetary role), which reports directly to the Prime Minister's office. The STA has line responsibility for the National Research Center for Disaster Prevention (NRCDP) in Tsukuba, which has a staff of 118 people, and coordinating responsibility for earthquake prediction and disaster prevention activities, which a small staff in Tokyo performs. The budget for earthquake prediction in Japan has increased from about \$1 million in 1965 to about \$38 million in 1981. As is typical in Japanese budgets, these figures exclude salaries and overhead for the 400 scientists and technicians directly involved. Thus they cannot be directly compared with U.S. figures, which do include salaries and overhead.

Earthquake prediction was established as a national goal in Japan in the early 1960s. It was given impetus by the 1965-1966 Matsushiro earthquake swarm, the 1968 Tokachi-Oki earthquake, and the 1971 San Fernando, California, earthquake. Finally, it became the focus of a major commitment in the mid-1970s when a magnitude 8± seismic gap was identified along the Nankai and Suruga troughs (in the Tokai region) offshore about 100 miles west of Tokyo. The Tokai region is a 14,000-km^2 area located on the major transportation corridor between

Tokyo and Osaka. This region is the site of major industrial facilities and has a population of about 6 million. Chinese reports of a successful prediction of the Haicheng earthquake in February 1975 were another factor in placing greater emphasis on earthquake prediction.

Identifying the Tokai seismic gap has led to the identification of land subsidence since the area's previous earthquake (the 1854 Ansei-Tokai earthquake) and to observations of horizontal compression in the area of the gap. Much of Japan's earthquake warning and preparedness efforts now focus on the Tokai region.

Much of the precursory earthquake data gathered by organizations for the Tokai region is telemetered to the headquarters of the Japan Meteorological Agency (JMA) in Tokyo, where the data are monitored for anomalies. The JMA data collection center is well equipped for data acquisition and display. It can determine epicenters in the Tokai region rapidly and has an automated circuit-checking system to determine the condition of equipment in the event of ground motion at the center itself. Whenever the center detects unusual increases in seismicity (threshold values have been set), changes in volume strainmeters, or other anomalies, it informs the Earthquake Diagnosis Committee (EDC).

If the EDC decides that the data warrant notification of higher authorities, the JMA Director-General transmits the earthquake prediction information to the Prime Minister, who in consultation with the cabinet decides whether to issue an earthquake warning statement. This process takes an estimated two and one-half hours. The government issues the earthquake warning statement to residents, public and private institutions, public corporations, and the prefectural governors. The Prime Minister is responsible for issuing the warning statement and for making public the scientific basis for the statement. The notification is made through the usual media (TV, radio, newspapers) and by loudspeaker trucks and loudspeakers activated by radio. If the earthquake does not occur after a considerable period and if the anomalous precursory phenomena disappear, the Prime Minister cancels the earthquake warning statement. Since it began in April 1977, the Tokai program has issued no false alarms, but it did not predict the magnitude 7.0 Izu-Oshima earthquake in 1978. The consensus is that a false alarm may be possible, but that a ''miss'' is unlikely in the Tokai region.

The National Research Center for Disaster Prevention and the national universities conduct much of the research on theoretical models related to earthquake prediction. The identification of the seismic gap in the Tokai region represents a long-term prediction; now Japan is concentrating on ways to make medium- and short-term predictions in this region. The effort has resulted in a massive amount of data that is little used outside of Japan and whose analysis has no precedent.

Earthquake Motions

In addition to the instrumentation used in the earthquake prediction program, networks of strong-motion accelerographs have been installed to quantify the distribution of strong earthquake ground motions in space and time. Although strong-motion accelerographs were first developed and installed in the United States, many are now manufactured and installed in Japan. Some are located to determine motions at rock and alluvial interfaces; others are associated with structures to determine the effects of soil-structure interaction. The Earthquake Research Institute, the Building Research Institute, the Public Works Research Institute, the Port and Harbour Research Institute, the Tokyo metropolitan government, other government agencies, universities, and private companies operate about 1,500 strong-motion instruments. As in the United States, there seems to be little coordination among the various organizations that install accelerographs except for special arrays.

The field observations of rock and ground motions complement laboratory studies of soil behavior and soil-structure behavior during earthquakes. These studies have produced some important advances in knowledge about the effect that structures have on local ground motion during an earthquake. Theoretical and analytical studies of the soil mechanics associated with earthquakes parallel the activities in the United States.

Seismic Hazard

Assessments of current earthquake hazards in Japan are generally based on historical earthquake data beginning in the year A.D. 679. For engineering purposes the seismic coefficient method is used. It is based on a macrozone map developed from the historical earthquake data, using magnitudes compiled by the Japan Meteorological Agency and incorporating attenuation of ground shaking with distance.

Measures of seismic hazard generally depend on the type of structure under consideration. For example, hazard for high-frequency systems is measured in terms of the peak acceleration; for low-frequency structures either the peak velocity or peak displacement is more appropriate. For important structures, however, the response spectrum is used. In Japan, ground conditions are generally divided into four categories—rock, diluvial deposits, alluvial deposits, and very soft ground. Appropriate correction factors account for local soil conditions. For major engineering systems, a project advisory committee specifies the design earthquake.

Generally, the acceptable seismic risk is based on the following thinking. Ground shaking that can reasonably be expected to occur during the life of the structure should not cause serious damage. For the very rare, extremely strong ground shaking, the structure should not collapse. Regional and local site factors take into account local soil conditions. The approaches in the highly seismic regions of the United States are similar to the foregoing but, perhaps, not quite as severe.

The Ministry of Construction is responsible for specifying the hazard levels for engineering design. In particular, the Public Works Research Institute is responsible for civil engineering structures, and the Building Research Institute is responsible for buildings. The Port and Harbour Research Institute of the Ministry of Transport is responsible for harbor systems, and the Ministry of International Trade and Industry is responsible for nuclear power plants.

Current research in hazard evaluation includes studies to revise the existing macrozone maps, using probabilistic hazard analysis that takes into account the source mechanism, fault dislocations, and other seismological and geological inputs of a given region. Studies to determine the seismicity and ground motions at a site are particularly important for major or critical facilities such as nuclear power plants. Research in Japan in this area includes topographic surveys of surface faulting and field research of fault activities at reactor sites. Seismic evaluations of sites in diluvial deposits are also planned, as are evaluations of underground structures in diluvial ground.

Building Codes

New building codes in Japan draw heavily upon the work and advice of governmental, university, and private researchers and designers. The seismic design of Japanese buildings has been changing markedly as a result of the intensified efforts in earthquake research. In 1980-1981 the building code of Japan underwent a major revision, the most extensive since the code was introduced in 1924. The main feature of the revision was the introduction of a two-phase design for earthquakes. The most important step in the second phase of design is evaluating the ultimate capacity of the structure for lateral loads.

The damages of structures caused by the Niigata earthquake in 1964, the Tokachi-Oki earthquake in 1968, and the San Fernando earthquake in 1971 stimulated a movement to improve and rationalize methods of earthquake-resistant design. As a direct consequence of this movement, the Ministry of Construction undertook a five-year project from 1972 to 1977 to establish a new method of rational seismic design for buildings. Such a method was proposed in March 1977, with the 1978 Miyagi-Ken-Oki earthquake providing impetus for it. In July 1980 a revision of the Enforcement Order of the Building Standard Law was released, to be enforced, along with supplementary documents, from June 1, 1981. Thus less than nine years were required to develop and enforce a major revision of the building code.

In comparison, the effects of the 1971 San Fernando earthquake in California resulted in a "National Workshop on Building Practices for Disaster Mitigation" in 1972. One recommendation suggested "the development of comprehensive seismic design provisions for buildings incorporating the current state of knowledge." The first step to implement this recommendation was an evaluation of the response spectrum approach to the seismic design of buildings. The Applied Technology Council (ATC) finished and published this study in September 1974. Following this, ATC began work on *Tentative Provisions for the Development of Seismic Regulations for Buildings*, which were published in 1978. Yet such provisions have not been incorporated into a seismic code. It should be noted, however, that in the United States local governments adopt the building codes, whereas in Japan the central government promulgates the code.

Architectural and Engineering Design

Earthquake engineering and structural dynamics research in Japan in general resembles that in the United States, combining computer and analytical studies with laboratory and field studies. However, differences in two areas are conspicuous.

First, Japanese research places considerably more emphasis on laboratory and field experimental studies. This emphasis on experimental applied research is perhaps a consequence of the Japanese philosophy of damage prevention and mitigation. For example, to certify any unusual structure, experimental evidence must demonstrate that the structure's seismic performance will be acceptable. For instance, even the 1981 earthquake provisions of the Japanese building code do not apply directly to buildings taller than 60 m. High-rise buildings are to be designed using special analyses, which may include time-history, nonlinear response analyses. The design is then subjected to technical review by the High-Rise Building Structure Review

Committee of the Building Center of Japan. Upon its recommendation, the Ministry of Contruction issues a special approval of the structural design. The ministry may also demand experimental evidence that the dynamic analysis can indeed reasonably well predict the structure's seismic performance. The agencies within the ministry also support large experimental research projects within their own research establishments and elsewhere. As discussed later in this chapter, these agencies have recently placed in service a number of newly constructed experimental research facilities.

Second, the private sector does a significant amount of research. Most of the research done by construction companies is of an applied nature and, therefore, has an immediate application in practice. Each of the six largest architectural, engineering, and construction firms maintains a large engineering research laboratory, for which there are no counterparts in the United States. Reportedly, the government suggested to these companies that they apply a certain percentage of their revenues to research laboratories. The larger of these laboratories have a work force of 400 to 500 people and excellent research and testing equipment.

The rapid use of its own research and development makes the parent company more receptive to the developments of others. Each major company has a technial staff that offers the client all required services, from initial conception to completed construction. These services cover such functions as basic planning studies (site reconnaissance and survey, social and economic survey and analysis, environmental impact assessment, economic and/or technical feasibility analysis), master planning, design, engineering construction, and construction management.

Research by government agencies, is mainly of an applied nature. However, the government also devotes significant efforts to fundamental research, and the results of this research are implemented rapidly. Universities are involved in applied and, to a large part, experimental research because private industry and governmental agencies sponsor their efforts. The implementation of research results obtained at universities follows the same pattern as that for government research.

Clearly, much more experimental research is being carried out in Japan than in the United States. Also, since experimental research costs more than other kinds of research, Japan is making a much bigger effort than is the United States.

Although Japanese earthquake engineering research places more emphasis on experimental investigations, it is not neglecting the theoretical and analytical aspects of the problem. The theoretical and analytical studies currently under way in Japan deal with such topics as the hysteretic behavior of steel and reinforced concrete structural systems, the response analysis of structures subjected to stochastic ground accelerations, and nonlinear soil-structure interaction. These analyses usually make use of finite element and other numerical methods, as in the United States. At this time, Japanese analytical capabilities appear to be more or less at the same level as in the United States.

The general tendency in Japan to emphasize experimental methods is particularly advantageous for the seismic design of equipment, as researchers in both Japan and the United States generally accept that testing is the only reliable way to evaluate the seismic performance of most equipment. The research laboratories of trade associations, of public utilities, and of equipment manufacturers have large vibration tables to evaluate the seismic response of full-scale equipment, and these organizations are able to commit the required resources of manpower and test specimens. The impact of these tests on implementation appears to be high, possibly because the user is closely involved with testing.

The same philosophy applies to the design and construction of nuclear power plants. Much effort is devoted to experimentally verifying system response. Proof-type tests are used to establish design levels, rather than arbitrary increases in the factors of safety. Successful construction of nuclear power plants requires a systematic integration of diverse technologies, and this task becomes considerably more difficult when the plant is located in a zone of high seismic risk. In Japan 23 nuclear power plants are presently in operation and 10 more are under construction. Most of these plants are located in zones of high seismic risk, and they have been built despite the increasing social and political opposition to nuclear power. It appears that research and development in the construction of nuclear power plants has tempered fears by demonstrating that it is possible to construct such plants safely.

A large test facility for experimentally verifying the components of nuclear power plants is nearly complete in Tadotsu, Shikoku. This NUPEC facility is expected to serve as an international test center and to help the sale to other countries of nuclear power plants designed in Japan.

Tsunami Research

Research on tsunamis addresses their generation, their transmission across the ocean, and their run up along the coast. Such research generally aims at improving tsunami warnings and the evaluation of hazards associated with tsunamis.

Considerable research effort has been applied to deriving methods that can determine ''tsunami magnitudes'' from seismic data and wave height data. Recent numerical simulations with computers have led to agreement between theoretical and experimental studies. The Japanese have used variably sized grids for the whole ocean, with depth contours near the coast, in designing local protective structures.

As with other earthquake hazards, the Japanese have taken the tsunami hazard very seriously. For example, in Ofunato they have constructed long breakwaters, with relatively small openings for transportation, to blunt the force of a tsunami before it reaches the shore of the inlet. Information on historical inundations of various ports is disseminated widely.

Numerical modeling has been done of historical tsunamis that originated near Japan. Such numerical modeling has also been done for tsunamis that reach Japan's continental shelf after passing the continental slope. These models include nonlinear effects, wave refraction and diffraction, and interactions with breakwaters and backwalls. Japan has pursued research on the run up of tsunamis and the resulting inundation much more vigorously than has the United States.

Earthquake Preparedness

Although the 1891 Nobi and 1923 Kanto earthquakes provided impetus for earthquake preparedness, not until quite recently did a national consensus develop in Japan that the country should make a major effort to improve earthquake preparedness. As noted earlier, the predicted magnitude 8 ± earthquake in the Tokai region west of Tokyo has been the main stimulus for this consensus. Japan's basic policy is formulated in the 1978 Large-Scale Earthquake Countermeasures Act, which outlines the basic steps required of the national, prefectural, and local governments once an area, such as the Tokai region, has been designated an ''intensified area'' (i.e., an area that can expect significant damage). These steps fall into two categories: (1) the intensified plan, which deals with medium- to long-term issues such as deploying instrumentation for earthquake prediction, identifying areas likely to receive great damage, reinforcing buildings, lifelines, and other structures, public education, and establishing procedures to make public announcements, and (2) the short-term plan, which deals with such issues as notification, evacuation, care and handling of refugees, medical treatment, traffic control, and repairs. The act also discusses emergency powers, financial assistance to carry out the plans, promotion of scientific research, and the procedure to issue the earthquake warning statement. In accordance with the act, the national government in 1980 issued its Basic Plan of Earthquake Disaster

Prevention for Areas Under Intensified Measures Against Earthquake Disaster for the "Tokai earthquake." This policy statement requires ministries, agencies, and local governments to prepare detailed plans and undertake preparedness activities. These two documents represent a careful attempt to deal with the prediction of a major earthquake in a densely populated, modern, highly industrialized society. The National Land Agency (NLA), located in Tokyo and reporting directly to the Prime Minister's office, supervises the national effort to prepare for the Tokai earthquake. A relatively small staff in the NLA's Earthquake Disaster Countermeasures Division and the related Disaster Prevention Policy Planning Division performs the supervision. Local agencies or the Ministry of Construction does most of the actual preparedness planning, land use planning, construction, etc. For the Tokai earthquake, approximately $1.5 billion is being expended in 1980-1984. Table 8 shows the breakdown of these expenditures.

Shizuoka Prefecture is the center of this preparedness effort. Typical efforts at preparedness include strengthening certain buildings, constructing water suppply cisterns in fire-prone areas, identifying and improving refugee routes and safe zones, stockpiling fire-fighting equipment, inspecting and rehabilitating flood control levees and highway and railway embankments and structures, constructing tsunami protection structures in certain locations, identifying landslide-prone areas, improving public communication facilities, and establishing a "transistor radio network." A network of over 4,000 voluntary organizations has been established that are equipped partially by the government and that engage in training and exercises in fire fighting, first aid, communications, and evacuee support. In 1980 $6 million was spent in Shizuoka Prefecture to purchase equipment for these groups.

Books and brochures at both adult and child levels are disseminated for public education. These explain the tectonics of the earthquake, the prediction and warning process, the possible postearthquake disasters and mitigation efforts, the damage expected in each city and town, what materials (food, water, etc.) to stockpile, and what actions to take to brace one's house, furniture, and other belongings. Shizuoka officials state that perhaps 50 percent of the people have some doubts, but that 90 percent are "going along" with their efforts to prepare for this major earthquake, which is expected sometime in the next 10 years.

Although Tokyo itself is outside of the Tokai intensified area, it expects to sustain damage when the Tokai earthquake occurs. Earthquake preparedness in Tokyo is taken seriously because of the city's experience in the 1923 earthquake. The Tokyo city government spent about $5 billion for disaster prevention in 1972-1977, and about $7

TABLE 8 Sources and Uses of 1980–1984 Expenditures for the Coming Tokai Earthquake

	Percentage		Percentage
Prefecture		Subject	
Kanagawa	15	Refugee centers	18
Yamanashi	20	Fire-fighting equipment	6
Najano	10	Highways	22
Shizuoka	55	Communications	4
TOTAL	100	Social welfare	4
		Public schools	24
Revenue Source		River control	4
National government	40	Coastal protection	5
Prefectural government	30	Erosion control	2
Local government	30	Security	5
TOTAL	100	Landslide protection	4
		Reservoirs	2
		TOTAL	100

billion is planned for 1978-1983. In comparison, the corresponding effort in the United States is perhaps $1 to $2 million per year.

Osaka is the third largest city in Japan, with about three million people in an area of 210 km² and a total population of 14 million people in the surrounding megalopolis. For the 1978-1987 period, Osaka is spending about $200 million annually for disaster mitigation (divided about equally between floods and earthquakes). Osaka is not in a predicted earthquake zone and thus is not covered by the special countermeasures law of 1978. Nevertheless, Osaka is making a major effort at earthquake disaster mitigation, one with many similarities to the programs under way in the Tokai regions.

Socioeconomic Aspects

Studies of the socioeconomic aspects of earthquakes are well advanced in Japan. They cover a broad spectrum, from estimates of damage to the proper format for earthquake warning statement, from the feasibility of using volunteer organizations to gather data about earthquake precursory phenomena to studies of how a population moves in the minutes following an earthquake warning statement. Detailed estimates of damage have been made for major cities. Besides the usual microzone maps, these include detailed quantification of the damage from likely earthquakes broken down by the agent of damage and the general structural category. Such estimates contribute to the formation of evacuation, refugee, repair, and contingency plans. This task is somewhat easier in Japan than in the United States due to Japan's longer recorded seismic history and the more uniform characteristics of its buildings and society.

Serious attempts have been made to quantify the indirect or secondary effects of earthquakes to buildings, their contents, agriculture, and society. Such studies are based on hard data and prove to be very useful, because their results can be both directly applied and used to explore similar effects in related sectors. These case studies require sizable funding to acquire and analyze the data.

Studies of postearthquake fires examine not only the aspects of the fire but such related problems as escape routes and the optimal use of fire-fighting resources. This fire problem is treated very seriously in Japan but is given very little consideration in the United States, even though the 1906 San Francisco earthquake generated a disastrous conflagration.

The titles of several recent earthquake-related socioeconomic studies are *Issues Associated with Earthquake Prediction Information* (which is concerned with the format and connotative content of earthquake warning statements); *Confusion Caused by Aftershock Warnings Following the 1978 Izu-Oshima Earthquake*; *Feasibility Study of Earthquake Precursor Observation System Employing Volunteer Organizations*; *Effective Recovery Strategy for Urban Systems After a Severe Earthquake*; *Study on Driver's Response in Earthquake Warning and the Effective Method for a "Preliminary Exercise" in Traffic Regulation*; *Study on the Effect of Broadcasting in Predicted Earthquake by Sham Radio-Program Experiment*; *Simulation of Person's Movement In and Around Yokohama Railroad Station in the Case of Earthquake Warning*; *Survey of Businesses' Intention to Remain Open in the Event of an Earthquake Warning*; *Study on How to Care for Shinkansen (Bullet Train) Passengers in the Case of an Earthquake Warning*; *Study on How to Care for Non-Resident Persons (in Izu Peninsula) in the Event of a Predicted or Non-Predicted Earthquake*.

Earthquake Education

Earthquake phenomena and earthquake engineering at the undergraduate level are taught in universities as part of courses in soil mechanics, structural dynamics, structural loads, and structural design. Architectural students also take such courses and, therefore, have a better understanding of earthquake engineering than do architects in the United States. The loads and effects of earthquakes on structures, including the definition of earthquake ground motions, are included in courses on structural loads, which also cover wind and snow loads.

Specialization in earthquake engineering starts at the graduate level. This training consists of architectural engineering (buildings) and civil engineering (other structures). The current number of Ph.D. graduate students specializing in earthquake engineering at Tokyo University (including the Institute of Industrial Sciences) is 18; the corresponding number at Kyoto University (including the Disaster Prevention Research Institute) is 10. Another 10 or so are studying at other universities, bringing the total to an estimated 40 or 50. This is more than are specializing in earthquake engineering in the United States. These Ph.D. students become teachers, research workers, and seismic design engineers for major projects.

The Japanese university system is organized by ''laboratories.'' A laboratory consists of a tenured professor, an associate professor, two research associates, and two technical staff members. Each laboratory is responsible for teaching and research in its area of specialty and each laboratory receives a regular research budget. The laboratories submit proposals to the Ministry of Education for special research funding in a procedure similar to that of the National Science Foundation in the United States vis-a-vis the universities. Private industry and public corporations in Japan also fund some university research.

The academic community and the practicing and industrial engineering community closely interact and cooperate in Japan. Graduates of the major universities continue to seek the advice of former professors. This tradition maintains close ties between former students working in industry and government and the academic faculties. University faculty members in earthquake engineering participate in many professional committees and in seminars and conferences organized by professional societies. Among such seminars are short courses on recent changes in building codes and standards, which include provisions for earthquake-resistant design.

Education of the general public includes steps to increase public awareness of the need for earthquake hazard mitigation. The government provides appropriate educational material on earthquakes and earthquake mitigation to grade school children as well as high school students. Special brochures describing the steps to take during an earthquake are distributed widely to the general public by, for example, the Disaster Prevention Section of the Tokyo metropolitan government. English versions of brochures are also available for foreigners.

The International Institute for Seismology and Earthquake Engineering (IISEE) was established in 1962. With the cooperation of the United Nations Development Program, it developed an instructional and research program for earthquake professionals from developing countries around the world. Since 1972 the Japanese government has fully supported IISEE, which is operated by the Building Research Institute at Tsukuba, at an annual cost of about $160,000, excluding salary and overhead costs.

IISEE trains 20 to 25 international participants per year in basic and advanced principles of earthquake engineering and seismology at no cost to the student. The normal training cycle takes 11 months, with 8 months of course lectures and on-site visits and three months for an individual research project. Some participants are allowed to spend a second year at IISEE to carry out advanced research on urgent problems in their respective countries. As of August 1981, IISEE had trained 491 participants from 49 countries. These are, in effect, technical ambassadors for Japanese engineering and research.

New Experimental Research Facilities

In addition to university and government earthquake research institutes and laboratories, many large industrial organizations maintain earthquake engineering research laboratories. This section discusses four major experimental research facilities to illustrate the vital concern in Japan for experimental verification or proof of theoretical and analytical results. Trade associations, construction companies, industries, and other organizations have recently built many other excellent new laboratories, but they are not covered in this report. However, the research work done by these other laboratories is as extensive as, and in some cases exceeds, that done by the following four facilities.

National Research Center for Disaster Prevention

During 1967-1970 the National Research Center for Disaster Prevention constructed a large-scale earthquake simulator (a shaking table) for a cost of about $3 million. This was the first research facility constructed in Tsukuba Science City. The 15-m by 15-m shaking table can provide either horizontal or vertical earthquake-type motions, one at a time. The maximum weight of a tested structure is 500 tons for horizontal motions and 200 tons for vertical motion. The maximum displacement amplitude of the table is 30 mm, the maximum velocity is 30 cm/s, and the maximum acceleration is 0.55 g for horizontal motions and 1 g for vertical motions at full load in the frequency range 0.1 to 50 Hz.

The center also plans to construct a three-dimensional 6-m by 6-m earthquake simulator with two horizontal axes and one vertical axis for simultaneous shaking. The maximum test load is 75 tons, its maximum amplitudes are ±200 mm for horizontal motion and ±100 mm for vertical motion, its maximum velocities are ±100 cm/s for horizontal motion and ±75 cm/s vertical motion, and its maximum acceleration is 1.2 g.

Building Research Institute

The Building Research Institute (BRI) has a large structural laboratory with two test floors (A and B) and a common reaction wall. It was constructed in Tsukuba during the late 1970s at a cost of about $8 million. Test floor A is 20 m wide and 25 m long and has a reaction wall 25 m high by 20 m wide with a maximum allowable shear force of 4,000 tons. Test floor B is 15.4 m wide and 20 m long and uses the same reaction wall as floor A. A second reaction wall 25 m high and 18 m wide with a maximum allowable shear force of 4,000 tons is planned that will be perpendicular to the first reaction wall, so that floor B can be used for triaxial loading. The U.S.-Japan Cooperative Research Program has used this facility in tests of a full-size seven-story reinforced concrete building.

BRI has another structural laboratory that has large static test machines and a 4-m by 4-m shaking table with one horizontal direction.

Public Works Research Institute

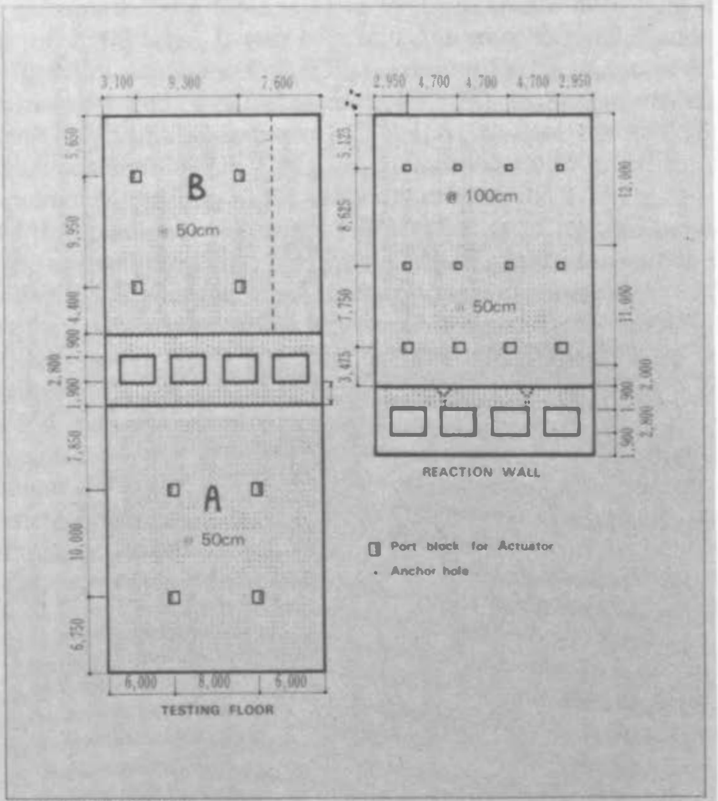
The Public Works Research Institute (PWRI) constructed the following facilities for earthquake engineering research in Tsukuba during the late 1970s at a cost of about $20 million. A 6-m by 8-m earthquake simulation facility has a maximum load capacity of 100 tons with a maximum stroke of ±75 mm, a maximum velocity of ±60 cm/s, and a maximum acceleration of 1.7 g. The institute also has four additional small shaking tables along one axis so that independent earthquake excitations can be applied to the piers of models of long-span bridges.

In addition, the institute has an earthquake engineering laboratory with a strong-room test pit for testing the nonlinear characteristics of structures and structure-soil specimens. The test pit is 20 m by 15 m, and the maximum alternating force is ±125 tons at a maximum speed of 1 m/s.

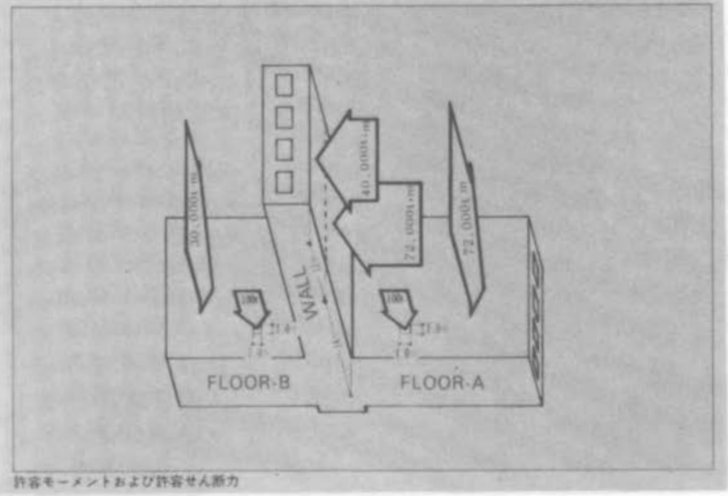
A 4-m by 4-m earthquake simulator for dams has recently been completed. It has a maximum load of 40 tons for model rock fill and concrete dams and a maximum acceleration of about 1.0 g. Dynamic triaxial compression-testing equipment adjacent to this new facility is used to determine the dynamic stress and strain properties of the dam materials.

Nuclear Power Engineering Test Center

The Nuclear Power Engineering Test Center (NUPEC) has constructed a large-scale, high-performance vibration table at Tadotsu, Shikoku. This facility will be completed in 1982 at a cost of about $200 million. It has been reported that the operating costs will be approximately $1

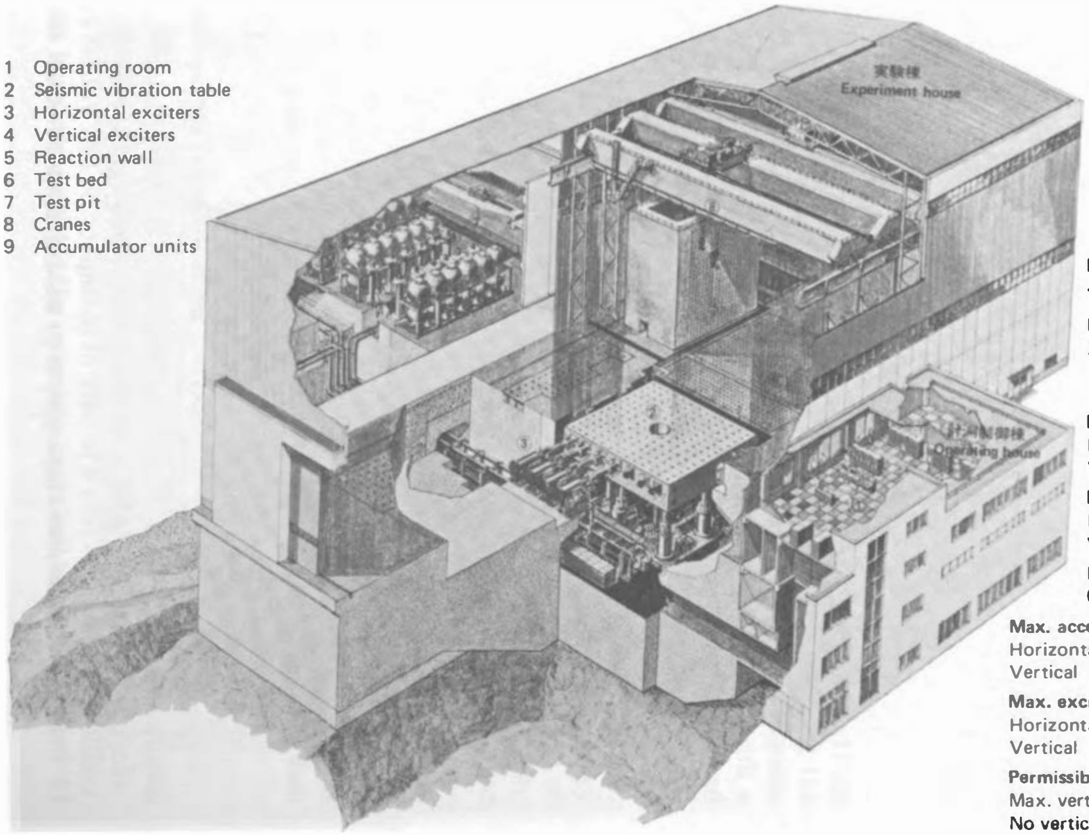


反力床・壁の平面図と立面図



許容モーメントおよび許容せん断力

The Large-Size Structural Laboratory of the Building Research Institute.



1 Operating room
2 Seismic vibration table
3 Horizontal exciters
4 Vertical exciters
5 Reaction wall
6 Test bed
7 Test pit
8 Cranes
9 Accumulator units

Max. loading capacity 1,000 t

Table size 15 m x 15 m

Excitation directions
X-Z axes simultaneously
X: Horizontal
Z: Vertical

Max. displacement
Horizontal ±200 mm
Vertical ±100 mm

Max. velocity
Horizontal 75 cm/s
Vertical 37.5 cm/s

Frequency range
0–30 Hz

Max. acceleration
Horizontal 2.72G(500 ton), 1,84G(1,000 ton)
Vertical 1.36G(500 ton), 0.92G(1,000 ton)

Max. excitation
Horizontal 3,000 ton f
Vertical 3,300 ton f

Permissible overturning moment
Max. vertical acceleration 6,500 ton f-m
No vertical excitation 12,000 ton f-m

The Nuclear Power Engineering Test Center facility.

million per month. The table is 15 m by 15 m with a maximum load capacity of 1,000 tons. It can be excited in one horizontal and the vertical direction simultaneously with maximum displacements of ±200 mm horizontally and ±100 mm vertically, with maximum velocities of 75 cm/s horizontally and one half that vertically. The maximum attainable accelerations are 1.84 g horizontally and 0.92 g vertically in the frequency range 0 to 30 Hz with a maximum load. For a 500-ton test load the maximum horizontal acceleration is 2.72 g and one half that in the vertical direction. Next to the shaking table are a static test floor and reaction wall for supplementary static experiments.

The center plans to use this facility mainly to test full-size or reduced-scale nuclear power plant components. About $100 million is allocated for the next five to seven years for dynamic tests at this facility. The first several tests will examine the containment vessel for a pressurized water reactor at a 1:3.7 scale, a 10-m-diameter by 10-long tank containment for liquefied petroleum gas, a primary loop for a boiling water reactor, the reactor core internals for a pressurized water reactor, the reactor core internals for a boiling water reactor, and so on. The first modern earthquake shaking table was developed in the United States, but in recent years Japan has progressed far beyond the United States in its shaking table capability.

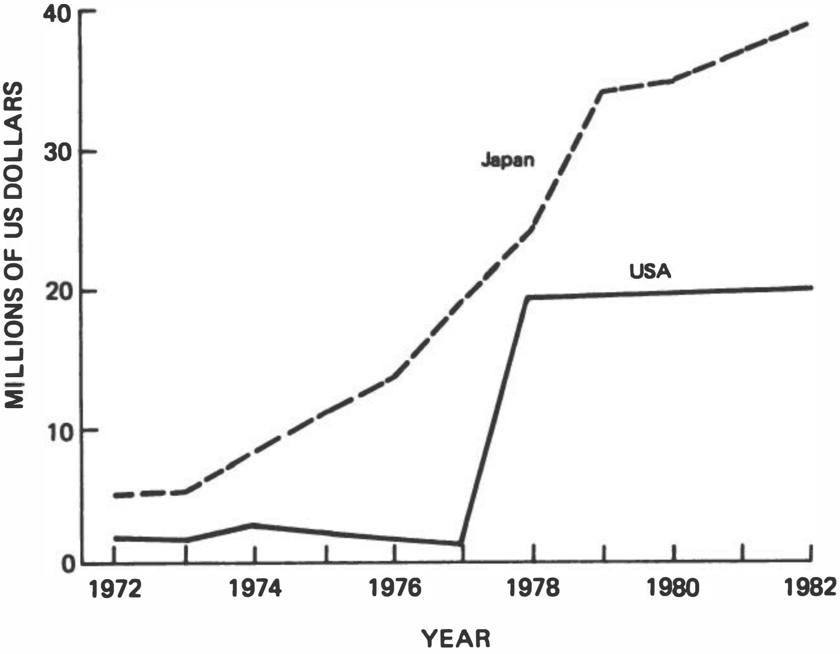
Research Funding

Although a detailed review and comparison of research funding for earthquake engineering in Japan and the United States would be desirable, the available information for both countries does not permit this, for several reasons. The data from Japan usually include direct research expenditures only, excluding personnel salaries, overhead, and other indirect costs, whereas the figures for the United States do include salaries and all indirect costs. The extensive efforts at earthquake hazard mitigation in the Tokai, Tokyo, and Osaka regions have no counterparts in the United States, so no comparison can be made. A major portion of earthquake engineering research in Japan is done in government research laboratories, industrial research laboratories, and major construction company research laboratories, whereas this is not the case in the United States.

The following comparisons separate the earthquake engineering research and evaluation efforts from the earthquake prediction efforts.

Earthquake Prediction

The research funds for earthquake prediction efforts in the United States have come from the U.S. Geological Survey and the National



Japan invests considerably more in earthquake prediction than does the United States, as shown in this figure. The funds for the United States are from the U.S. Geological Survey and the National Science Foundation. The totals for Japan exclude salaries and overhead.

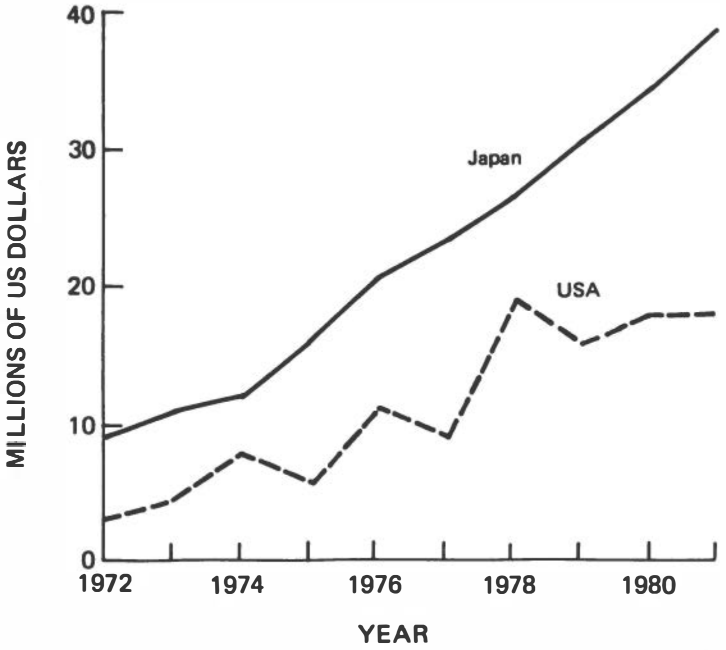
Science Foundation (Geophysics). These totals include salaries and indirect costs. They show that the earthquake prediction efforts in Japan have been significantly greater than corresponding efforts in the United States, perhaps four times greater.

Earthquake Engineering Research and Evaluation

The National Science Foundation is the major source of funding for earthquake engineering in the United States. The U.S. figures do not include funds allocated directly to other government agencies such as the National Bureau of Standards and Department of Defense because their contributions to earthquake engineering research are relatively small. They also do not include research funds provided through the Nuclear Regulatory Commission (NRC), as these seem to be devoted mainly to verifying NRC requirements and procedures. Similarly, the Japanese totals do not include funds for nuclear power research. The research funds in Japan come from the following agencies: Building Research Institute, Public Works Research Institute, Port and Harbour Research Institute, National Research Center for Disaster Prevention, Tokyo University, Kyoto University, Tohoku University, Osaka University, Tokyo Electric Power Company (nonnuclear), Central Research Institute of Electrical Power Industry (nonnuclear), and six of the major private construction companies. A number of universities are not included, nor are industrial research laboratories. Except for some of the construction company data, these numbers do not include costs of personnel, facilities, or indirect costs. Nor do the data from Japanese universities include research funds provided by private companies or public corporations.

It is difficult to make a precise comparison, but the Japanese effort in earthquake engineering research appears to be approximately four to five times greater than the U.S. effort, and this does not take into account the $200 million shaking table facility at the Nuclear Power Test Center.

In January 1982 the Prime Minister's office and Bureau of Statistics in Japan reported the distribution of research expenditures as 25 percent by universities, 15 percent by public research institutes, and 60 percent by private companies in the fiscal year 1981 (April 1980-



Japan spends more on earthquake research and evaluation, excluding earthquake prediction, than does the United States. The totals for the United States are from the National Science Foundation and include salaries and overhead. The totals for Japan are from specific agencies and exclude salaries and overhead (except for some construction companies).

March 1981). The data gathered suggest that these percentages are also representative of the distribution of effort in earthquake engineering research. This supports the belief that the reported research in universities (excluding private funds) significantly underestimates the total university efforts and thereby the total Japanese efforts.

Conclusions

It is clear that a much greater effort is being made in Japan to cope with destructive earthquakes than is being made in the United States. Approximately four times as much funding is devoted to earthquake prediction in Japan than is allocated in the United States. Furthermore, the Japanese funding for earthquake engineering research is approximately four or five times the U.S. funding. The heavy funding in Japan of experimental research in earthquake engineering is especially striking. The Japanese government demonstrates a deep concern about earthquakes and earthquake disasters, much more than does the U.S. government. This is no doubt due to the fact that destructive earthquakes have devastated the capital city twice in the last 150 years.

It is generally accepted in Japan that the earthquake hazard is real, imminent, and can be expected to have a serious effect on each citizen's life. With this viewpoint, it is not surprising that all levels of government, earthquake professionals, and the public fully support earthquake prediction, hazard mitigation, and postearthquake response planning. The development of the technical, political, and social capabilities in the earthquake field are broadly distributed in Japan and are actively transmitted to other countries around the world through governmentally supported assistance programs and private industrial developments. Approximately $2.5 billion per year is being expended on earthquake preparedness measures, an amount that dwarfs the modest U.S. effort.

In addition to the differences in funding between the U.S. and Japanese earthquake hazard mitigation efforts, there are striking differences in how well private citizens and local government officials are mobilized and in the effort that private construction companies and industrial research laboratories devote to the problem.

Because of the greater level of earthquake engineering research in Japan, particularly in the experimental research that provides basic data for analytical research, the world center of earthquake engineering research can be expected to move to Japan. If the United States is to stay competitive in earthquake engineering, its earthquake hazard mitigation program will have to be substantially increased.

Appendix A

Biographical Sketches of Committee Members

GEORGE W. HOUSNER is C. F. Braun Professor of Engineering at the California Institute of Technology. He received a B.S. in Civil Engineering from the University of Michigan and a Ph.D. in the same field from the California Institute of Technology, where he has been on the faculty since 1945. He has served as President of the International Association for Earthquake Engineering and as President of the Earthquake Engineering Research Institute. He has authored three textbooks and more than 100 technical papers. He is a member of the National Academy of Sciences and of the National Academy of Engineering and was Chairman of the National Research Council's Committee on Earthquake Engineering Research, 1967-1969.

MIHRAN S. AGBABIAN is President of Agbabian Associates, an engineering and consulting firm in El Segundo, California. He has M.S. and Ph.D. degrees from the California Institute of Technology and the University of California at Berkeley, respectively, is a registered structural and mechanical engineer in California, and is licensed in three other states. Prior to founding his company in 1962, he was employed by the Bechtel Corporation, the Ralph M. Parsons Company, and John K. Minasian in Pasadena, California. He is a fellow of the American Society of Civil Engineers and Chairman of the Committee on Shock and Vibratory Effects. He is also President-Elect of the Earthquake Engineering Research Institute, Chairman of the Earthquake Hazard Mitigation Advisory Subcommittee of the National Science Foundation, Chairman of the Program Committee for the Eighth World Conference on Earthquake Engineering, and a member of the National Academy of Engineering.

CHRISTOPHER ARNOLD is President of the Building Systems Development Corporation in San Mateo, California. He has a diploma from Cambridge University in Political Philosophy and Economics. His B.A. and M.A. degrees in architecture are from London and Stanford Universities, respectively. He is a registered architect in California, New York, and Arizona and is a member of the Royal Institute of British Architects.

Ray W. Clough is Professor of Civil Engineering at the University of California, Berkeley, and has been on the engineering staff there since 1949, serving as director and assistant director of the Earthquake Engineering Research Center since 1973. He has M.S. and Ph.D. degrees in Structural Engineering from the Massachusetts Institute of Technology and an Honorary Doctor of Technology from Chalmers University in Sweden. He is a member of the National Academy of Sciences and the National Academy of Engineering, was a member of the National Research Council's Committee on Earthquake Engineering, 1967-1968, and was Chairman of the National Research Council's Committee on Natural Disasters.

Lloyd S. Cluff is Vice President, Principal, and Director of Woodward Clyde Consultants in San Francisco, California. He graduated from the University of Utah in 1961 with a major in geology. He has served as Vice President of the International Association of Engineering Geologists, President of the Association of Engineering Geologists, and President of the Seismological Society of America. He has served on many earthquake advisory panels, including those advisory to the U.S. Geological Survey and to the National Science Foundation. He is also a member of the National Academy of Engineering.

William J. Hall is Professor of Civil Engineering at the University of Illinois in Urbana-Champaign. He has M.S. and Ph.D. degrees in Civil Engineering from the University of Illinois and a B.S. degree from the University of Kansas. He has served on many National Research Council committees and was Chairman of the Panel on Earthquake Problems Related to the Siting of Critical Facilities of the Committee on Seismology. He has served as Chairman of the Structural Division of the American Society of Civil Engineers and is a member of the National Academy of Engineering.

Robert D. Hanson is Professor and Chairman of the Division of Civil Engineering at the University of Michigan. He received a B.S. and a M.Sc. in Civil Engineering from the University of Minnesota and a Ph.D. from the California Institute of Technology. He was Vice President of the Earthquake Engineering Research Institue. He served as UNESCO expert and Chief Technical Advisor at the International Institute of Seismology and Earthquake Engineering in Tokyo and is currently U.S. Technical Coordinator for the U.S.-Japan Cooperative Earthquake Engineering Research Project. He has also been active in the committees of the American Society of Civil Engineers and is a registered professional engineer in Michigan.

Donald E. Hudson is the Fred Champion Professor of Engineering and Chairman of the Department of Civil Engineering at the University of Southern California in Los Angeles. He is President of the International Association of Earthquake Engineering, a past president of the Seismological Society of America, and a member of the American Society of Mechanical Engineers, the Earthquake Engineering Research Institute, and the Society for Experimental Stress Analysis. He was a member of the National Research Council's Committee on Earthquake Engineering Research, 1967-1969, and is a member of the National Academy of Engineering.

JOSEPH PENZIEN is Professor of Structural Engineering at the University of California, Berkeley. He has a Sc.D. degree from the Massachusetts Institute of Technology and is a registered civil engineer in California and Washington. He was Director of the Earthquake Engineering Research Center at the University of California, Berkeley, during 1968-1973 and 1977-1980. He has authored over 150 technical papers and reports, most of them in earthquake engineering, and has coauthored (with R. W. Clough) a textbook, *Dynamics of Structures*. He is a member of the National Academy of Engineering, the American Society of Civil Engineers, the Earthquake Egnineering Research Institute, the Seismological Society of America, the American Concrete Institute, and the Structural Engineers Association of California. In 1982 he was appointed Chairman of the Steering Committee for the Eighth World Conference on Earthquake Engineering.

RALPH H. TURNER is Professor of Sociology and Anthropology at the University of California, Los Angeles, and has served as Chairman of the Department of Sociology. He received a Ph.D. in Sociology from the University of Chicago and was a Fulbright research fellow at the University of London. He is a member of the American Sociological Association and was President in 1968-69. He has authored or coauthored eight books and over 100 other publications in the social sciences and has studied the social impacts of national disasters. He was Chairman of the National Research Council's Panel on Public Policy Implications of Earthquake Prediction in 1974 and 1975, a member of the National Academy of Science's Earthquake Prediction Delegation to the People's Republic of China in 1976, and coauthored *Earthquake Threat: The Human Response in Southern California* (1979).

ANESTIS S. VELETSOS is the Brown and Root Professor in the Department of Civil Engineering at Rice University in Houston, Texas, and has served as Chairman of the department. He has Ph.D. and M.S. degrees in Structural Engineering from the University of Illinois, Urbana-Champaign, and served on the faculty of that institution from 1955 to 1964. He has served as Vice President of the Earthquake Engineering Research Institute and Chairman of the Engineering

Mechanics Division of the American Society of Civil Engineers. He is a member of the National Academy of Engineering.

Robert V. Whitman is Professor of Civil Engineering at the Massachusetts Institute of Technology. He has served on many earthquake engineering advisory committees and was Chairman of the National Science Foundation's Earthquake Hazard Mitigation Subcommittee of the Advisory Committee for Engineering. He has been a Director and Vice President of the Earthquake Engineering Research Institute and Chairman of the American Society of Civil Engineers' Technical Council for Lifeline Earthquake Engineering. He is a researcher and consultant in soil mechanics, soil dynamics, earthquake engineering, and seismic risk and is a member of the National Academy of Engineering.

Appendix B

Acknowledgments

Many individuals assisted the Committee in this study. Members of each working group actively participated in discussions with the respective working group chairman in preparing a draft chapter for the report. Corresponding members of the working group reviewed the draft chapter and made recommendations for improvements. Liaison representatives were asked to review Chapters 2 through 11 and comment on the factual accuracy of the working groups' findings, particularly with respect to those findings of major relevance and interest to each representative's agency. The Committee gratefully acknowledges the contributions of all who assisted.

Working Groups

Applications of Past Research

Members

Mihran S. Agbabian, *Chairman,* Agbabian Associates
Paul C. Jennings, California Institute of Technology
LeVal Lund, Department of Water and Power, City of Los Angeles
Haresh C. Shah, Stanford University
Roland L. Sharpe, Engineering Decision Analysis Corporation, Palo Alto, California
Kenneth H. Stokoe, University of Texas, Austin

Corresponding Members

William Armstrong, Naval Civil Engineering Laboratory
Robert Fuller, Department of Housing and Urban Development

Assessment of Earthquake Hazard

Members

Lloyd S. Cluff, *Chairman,* Woodward Clyde Consultants, San Francisco, California

Clarence R. Allen, California Institute of Technology
George E. Brogan, Woodward Clyde Consultants, Los Angeles, California
James R. Davis, California State Geologist
Otto Nuttli, St. Louis University
David B. Slemmons, University of Nevada, Reno

Corresponding Members

Walter W. Hays, U.S. Geological Survey, Reston, Virginia
Haresh C. Shah, Stanford University
Robert E. Wallace, U.S. Geological Survey, Menlo Park, California

Earthquake Ground Motion

Members

Donald E. Hudson, *Chairman,* University of Southern California
Clarence R. Allen, California Institute of Technology
Keiiti Aki, Massachusetts Institute of Technology
Wilfred D. Iwan, California Institute of Technology

Corresponding Members

Bruce A. Bolt, University of California, Berkeley
A. Gerald Brady, U.S. Geological Survey, Menlo Park, California

Soil Mechanics and Earth Structures

Members

Robert V. Whitman, *Chairman,* Massachusetts Institute of Technology
I. M. Idriss, Woodward Clyde Consultants, Santa Ana, California
Frank E. Richart, Jr., University of Michigan
Ronald F. Scott, California Institute of Technology
H. Bolton Seed, University of California, Berkeley

Corresponding Members

William Marcuson, Waterways Experiment Station, Mississippi
Leslie T. Youd, U.S. Geological Survey, Menlo Park, California

Analytical and Experimental Structural Dynamics

Members

Ray W. Clough, *Chairman,* University of California, Berkeley

Asadour H. Hadjian, Bechtel Power Corporation, Los Angeles, California
Gary C. Hart, University of California, Los Angeles, California
Neil M. Hawkins, University of Washington
Jose M. Roesset, University of Texas, Austin

Corresponding Members

Vitelmo V. Bertero, University of California, Berkeley
Dixon Rea, University of California, Los Angeles
Edward L. Wilson, University of California, Berkeley

Earthquake Design of Structures

Members

William J. Hall, *Chairman*, University of Illinois, Urbana-Champaign
Christopher Arnold, Building Systems Development, Inc., San Mateo, California
Henry J. Degenkolb, H.J. Degenkolb Associates, Engineers, San Francisco, California
Wilfred D. Iwan, California Institute of Technology
James O. Jirsa, University of Texas, Austin
Roy G. Johnston, Brandow and Johnston & Associates, Los Angeles, California
Clarkson W. Pinkham, S. B. Barnes & Associates, Los Angeles, California
Mete A. Sozen, University of Illinois, Urbana-Champaign

Corresponding Members

Melvin L. Baron, Weidlinger Associates, New York, New York
James E. Beavers, Union Carbide Corporation, Oak Ridge, Tennessee
Vincent R. Bush, International Conference of Building Officials, Whittier, California
Kent Goering, Defense Nuclear Agency
Paul C. Jennings, California Institute of Technology
Don A. Linger, Defense Nuclear Agency
Anshel J. Schiff, Purdue University
Roland L. Sharpe, Engineering Decision Analysis Corporation, Palo Alto, California
George Sherwood, U.S. Department of Energy
Richard N. Wright, National Bureau of Standards

Seismic Interaction of Structures and Fluids

Members

Anestis S. Veletsos, *Chairman,* Rice University, Houston
Robert G. Bea, PMB Systems Engineering, Inc., San Francisco, California
Anil K. Chopra, University of California, Berkeley
Robert L. Wiegel, University of California, Berkeley
Robert S. Wozniak, Chicago Bridge & Iron, Oak Brook, Illinois

Corresponding Members

Medhat A. Haroun, University of California, Irvine
Frederick Raichlen, California Institute of Technology
Glenn S. Tarbox, R. W. Beck and Associates, Seattle
Damodaran Nair, Brown & Root, Inc., Houston

Social and Economic Aspects

Members

Ralph H. Turner, *Chairman,* University of California, Los Angeles
Harold Cochrane, Colorado State University
Linda Nilson, University of California, Los Angeles
Alan J. Wyner, University of California, Santa Barbara

Corresponding Members

Thomas Drabek, University of Denver
James Huffman, Natural Resources Law Institute, Portland, Oregon
Dennis Mileti, Colorado State University
Joanne Nigg, Arizona State Univeristy
Richard S. Olson, University of Redlands, California
Risa Palm, University of Colorado
William J. Petak, University of Southern California
E. L. Quarantelli, Ohio State University
James D. Wright, University of Massachusetts

Earthquake Engineering Education

Members

Joseph Penzien, *Chairman,* University of California, Berkeley
James Anderson, University of Southern California
Glen V. Berg, University of Michigan

John Loss, University of Maryland
Lawrence G. Selna, University of California, Los Angeles

Corresponding Member

James M. Gere, Stanford University

Research in Japan

Members

Robert D. Hanson, *Chairman,* University of Michigan
Alfredo H. S. Ang, University of Illinois, Urbana-Champaign
Vitelmo V. Bertero, University of California, Berkeley
Joseph Penzien, University of California, Berkeley
Charles Scawthorn, Dames & Moore, Civil Engineers, San Francisco
Masanoba Shinozuka, Columbia University

Corresponding Members

Christopher Arnold, Building Systems Development, Inc., San Mateo, California
Paul C. Jennings, California Institute of Technology
E. L. Quarantelli, The Ohio State University
Anshel J. Schiff, Purdue University
James K. Wight, The University of Michigan
Peter Yanev, EQE, San Francisco, California

Liaison Representatives

John B. Scalzi, National Science Foundation
Roger D. Borcherdt, U.S. Geological Survey; Alternate, Gerald Brady
Ugo Morelli, Federal Emergency Management Agency
George Sherwood, Department of Energy
Leon L. Beratan, Nuclear Regulatory Commission
Don A. Linger, Defense Nuclear Agency; Alternate, Kent Goering
Richard F. Davidson, U.S. Army Corps of Engineers
Joseph V. Tyrrell, Naval Facilities Engineering Comand; Alternate, William Armstrong
J. Lawrence Von Thun, U.S. Bureau of Reclamation; Alternate, Raymond Gettel
Charles F. Scheffey, Federal Highway Administration

G. Robert Fuller, Department of Housing and Urban Development
Richard D. McConnell, Veterans Administration; Alternate, Roy G. Johnston
Edgar V. Leyendecker, National Bureau of Standards
Paul C. Jennings, Earthquake Engineering Research Institute
W. D. Iwan, Universities Council for Earthquake Engineering Research
Al Kuentz, American Iron and Steel Institute
Vincent R. Bush, International Conference of Building Officials
James R. Smith, Building Seismic Safety Council

NRC NAS NAE IOM

National Academy Press

The National Academy Press was created by the National Academy of Sciences to publish the reports issued by the Academy and by the National Academy of Engineering, the Institute of Medicine, and the National Research Council, all operating under the charter granted to the National Academy of Sciences by the Congress of the United States.