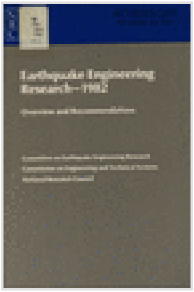

Earthquake Engineering Research--1982: Overview and Recommendations (1982)

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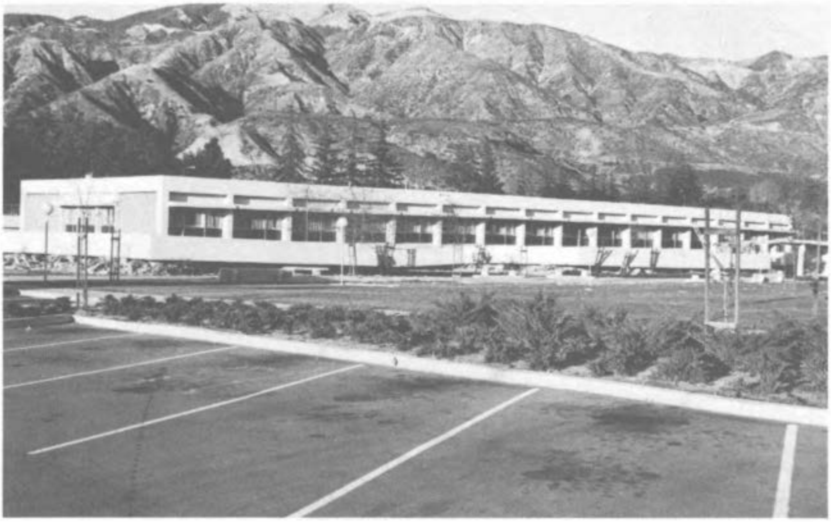

The new hospital building shown in the top photograph was designed in 1968 according to the earthquake requirements of the building code, but it did not have sufficient strength to resist the magnitude 6.5 San Fernando, California, earthquake of 1971. The building was essentially a heavy mass supported on slender columns that disintegrated during the earthquake and crushed the first floor (bottom photograph). Fortunately, there were no occupants in the first story, though several people were on the second floor and rode the building down safely.

Earthquake Engineering Research—1982

Overview and Recommendations

Committee on Earthquake Engineering Research
Commission on Engineering and Technical Systems
National Research Council

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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.

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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.

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*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

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*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.

Executive Summary

During the past 200 years, large and destructive earthquakes have occurred in the United States. The most important of these were centered near New Madrid, Missouri, in 1811-1812; Charleston, South Carolina, in 1886; San Francisco, California, in 1906; and Anchorage, Alaska, in 1964. In addition, many smaller yet damaging earthquakes have struck different parts of the country. As this seismic history makes clear, the United States has a serious earthquake problem, one that the growth of population, increased urbanization, and the development of high-technology industries have markedly exacerbated.

Public safety and welfare require not only that homes and ordinary commercial buildings be able to resist earthquakes but that special structures and facilities, industrial processes, public utilities, and other structures and systems also be able to withstand earthquake shaking. Accomplishing this requires research to provide basic knowledge about destructive earthquakes, to build up an understanding of how man-made works behave when subjected to ground shaking, to originate appropriate methods of analysis, to develop an expertise in designing structures and facilities that can withstand strong ground shaking, and to make appropriate plans and preparations.

Because disastrous earthquakes occur relatively infrequently in any one country, the hazard tends to be downplayed. For example, although China has a 2,000-year history of destructive earthquakes, its building code zoned the industrial city of Tangshan (60 miles east of Beijing) for no earthquake design. On July 28, 1976, this city of about one million inhabitants was leveled by a magnitude 7.8 earthquake, which left several hundred thousand people dead. Six years later, despite a strong rebuilding effort, the city is only about half rebuilt.

Learning from this disaster, China has in recent years built up a very strong effort in earthquake engineering research. Today China's effort is greater than that in the United States. The earthquake engineering research program in Japan, another country with a severe earthquake problem, is also much larger than the U.S. program, particularly in experimental research.

The U.S. effort in earthquake engineering research was very small until about 10 years ago, when the Earthquake Hazard Reduction Program was established at the National Science Foundation. During the past decade a productive earthquake engineering research program has developed in the United States and has played a leading role in international seismic engineering. The results of this research have been effectively applied to many large and important projects that have had earthquake safety as a major consideration. Examples of such projects include high-rise buildings, major dams, electrical power facilities, nuclear power plants, liquefied natural gas facilities, offshore drilling platforms, major oil and gas pipelines, and bridges. In addition, certain high-technology organizations that have recognized that they have earthquake problems, including IBM, AT&T, Exxon, General Electric, Lockheed, Dupont, Bechtel, and others, have applied the results of earthquake engineering research, as have several large insurance companies such as Aetna Life and Travelers. The results of research have also been applied to improve the safety of some military facilities, and they have been incorporated in special design codes for bridges, petroleum storage tanks, offshore platforms, and other structures. Furthermore, many of the foregoing developments have had an influence in seismic regions worldwide.

Ordinary structures, such as dwellings and commercial buildings, are designed according to the seismic requirements of building codes. These requirements are simplified rules for design that can be easily applied. Damage in past earthquakes has sometimes shown that the requirements were too simple, and changes were then made in the codes. But substantial changes in codes occur only slowly and after much deliberation, because codes govern very large investments per year in construction.

Nevertheless, major improvements based on earthquake engineering research have been made in building codes. This can be seen by comparing present code requirements with those first adopted in 1933 following the disastrous Long Beach, California, earthquake. Very little was known about earthquake shaking and earthquake engineering in 1933, so the requirements merely stated that all buildings should be designed to resist a static horizontal force equal to a fixed percentage (8 percent) of their weight. Present-day code requirements specify design forces that depend on the degree of seismic hazard, the natural period of vibration of a structure, the kind of ground on which it is sited, the ductility of its materials of construction, and other factors. The result is improved earthquake design.

These modern simplified requirements have not yet been thoroughly tested by a strong earthquake. In addition, most buildings in U.S. cities were constructed under outdated code requirements, and many were built when seismic requirements were not enforced. As a result, a strong earthquake occurring close to any American city will certainly cause severe damage and deaths.

A strong experimental program on materials and structures subjected to forces and deformations representative of earthquake conditions is needed. This program could provide the needed information without waiting for a destructive earthquake to demonstrate the need. Research should also seek to develop methods of seismic design that will in the long term result in cities filled with structures whose safety will eliminate the earthquake problem.

Postearthquake Investigations

The occurrence of a strong earthquake can be viewed as a full-scale experiment, one that confirms methods of seismic design or demonstrates defects in planning, design, and construction. Past earthquakes have taught important lessons, but these events have not received the study they deserved because of lack of preparation, lack of manpower, and lack of funding. Future U.S. and foreign earthquakes should be more thoroughly studied. Preparations should be made for recording relevant motions and strains of structures, and these instrumental records should be analyzed in depth. Preparations should also be made for coordinated postearthquake inspections that lead to preliminary reports. In-depth studies should then be made of significant structural behavior and of other aspects of the earthquake that are relevant to hazard reduction. It is important that prompt and adequate funding be available for postearthquake investigations and that preearthquake planning be organized.

Assessment of Earthquake Hazard

A key element in reducing earthquake hazard is the ability to assess seismic hazard reliably. Appropriate levels of earthquake design can then be established for important projects, and reliable seismic zoning maps can be prepared for building codes. Such assessments require study of the historical earthquake record, of faults that have generated earthquakes in the past, of recorded ground motions, of probabilistic methods of analysis, and of other subjects. Although hazard assessments have made progress, giving a better understanding of the situation, considerable uncertainty is involved and therefore their reliability needs to be improved.

Recording and Analyzing Earthquake Ground Motions

One of the most important components of earthquake information is the recording of strong ground shaking near the center of an earthquake. Such recordings are needed to understand the behavior of structures during the earthquake and to estimate reliably the ground shaking that future earthquakes might produce. In the past the strong ground motions of most earthquakes have not been recorded. This was the case, for example, in the great Alaska earthquake of 1964 and in the disastrous Tangshan, China, earthquake of 1976. A few recent earthquakes have been well recorded, but this is the exception rather than the rule.

There is a need to install and to plan for strong-motion instruments in selected locations. These instruments should be placed in configurations that provide the information needed to improve hazard assessments and the design of structures. Research and development should be undertaken to modernize and improve strong-motion instruments so that they can better record and process ground motion data. A national earthquake engineering committee should be established with one of its tasks being to lay out and coordinate a U.S. national strong-motion program. This program should seek to coordinate the installation of instruments and the processing and dissemination of strong-motion data. The United States should also undertake cooperative programs with other seismic countries to exchange recorded data and other relevant information.

Soil Mechanics and Earth Structures

Earthquake-induced landslides, soil liquefaction, and failure of earth structures have caused extreme damage in past earthquakes. In recent years research has made progress in understanding the earthquake dynamics of soils and earth structures, but this complex subject needs further study. Among the subjects requiring particular attention are the influence of local ground characteristics on earthquake shaking, the physical properties of soils under dynamic stresses and strains up to the point of failure, the dynamics of earth structures, and the dynamic interaction between the soil and a superposed structure.

Analytical and Experimental Structural Dynamics

Research on structural dynamics has led to improved practical methods of analysis and design that are now widely used. However, these methods do not apply to complex structures or to structures undergoing large nonlinear (damaging) strains. The upper-bound intensity of shaking is expected to produce large nonlinear strains in structures, so it is important that a strong research effort investigate the problem of strongly nonlinear motion in structures. This effort should include a strong component of experimental research on the nonlinear behavior of materials and structural components. Selected buildings should be instrumented to record nonlinear behavior during earthquakes, and the records should be studied to explain structural properties during nonlinear motion.

Seismic Interaction of Structures and Fluids

The interaction of structures and fluids introduces complications during earthquakes. The dynamic forces exerted by a fluid—such as the water in a reservoir upon the face of a dam; oil, gasoline, or liquefied natural gas on the walls of a large storage tank; ocean water on an offshore tower; or the surges of a tsunami on coastal structures—must be evaluated and taken into account in designing structures. During the past decade significant progress has been made in understanding the problem of fluid-structure interaction. For example, the seismic design of dams no longer considers just a static analysis of a dam but now includes a dynamic analysis that takes into account the dam's earthquake shaking and vibratory motions. Similar methods are used for the seismic design of large petroleum storage tanks. However, research is still needed on the performance of new and unusual structures, such as offshore towers in 1,000 ft or more of water, large petroleum storage tanks whose diameter exceeds the length of a football field, tanks for storing liquefied natural gas, and dams of unusual height or configuration. There is also a need for better assessments of tsunami hazard that consider coastal run up and hydrodynamic forces.

Social and Economic Aspects

A destructive earthquake affects individuals through deaths, injuries, and psychological distress. It hampers the functioning of public utilities, communication systems, and local governments. It influences industrial, commercial, financial, and insurance operations. Recovery efforts following a major earthquake can extend over years, putting unusual strains on the social fabric. Preparing for an earthquake also places heavy demands on government agencies. Even an earthquake prediction, true or false, can greatly influence a society.

The social and economic impacts of earthquakes, and the actions that should be taken before and after an event, require study and explication. Studies should also be made of foreign experiences. For example, Japan now has under way a major preparation program for an expected large earthquake; China is still recovering from a disastrous and unexpected earthquake; and the 1972 Managua, Nicaragua, earthquake caused a large number of deaths, resulted in economic losses approximately equal to the country's gross national product, and had severe social and political repercussions. Valuable lessons could be learned from such events, even though the conditions in foreign countries differ from those in the United States.

In recent years some state and local governments in the more highly seismic regions of the United States have begun to undertake land use planning, earthquake preparations, and disaster planning, but the effort still has far to go. Regions in which large but very infrequent earthquakes are expected to occur, such as the Missouri-Tennessee and the South Carolina areas, face special problems in this regard.

Earthquake Engineering Education

The impact of a strong earthquake on a city depends almost entirely on the degree to which earthquake engineering has prepared for the event. If all the city's structures and facilities have been planned, designed, and constructed in such a way that little damage is incurred, the earthquake will have only a minor effect. Therefore the earthquake problem can be solved if research has developed the proper procedures and if these procedures have been used long enough for unsafe buildings and facilities to be replaced by properly designed ones. This long-term solution is the objective of earthquake engineering, and it should be the objective of federal, state, and local governments.

Essential ingredients in a program to accomplish this objective are research workers, teachers, seismic design engineers, seismic planners, and other professionals. Having adequate numbers of these requires a continuing educational program. The number of Ph.D. graduates specializing in earthquake engineering is not now sufficient to meet the needs of research and teaching. A substantial portion of the Ph.D. graduates are foreign students, many of whom return to their homelands. A substantial fraction are also recruited by industry and government. Many who might otherwise pursue advanced studies are recruited by industry after receiving their B.S. or M.S. degrees, attracted by generous salaries and fringe benefits. To meet the needs of earthquake engineering research and teaching requires an incentive program for U.S. students to work for their Ph.D. degrees.

Education in earthquake engineering requires a knowledge of seismology, dynamics, vibration theory, properties of materials, and applied mathematics. Thus an undergraduate student is not prepared to study the subject. This means that most design engineers will not have studied earthquake engineering at their universities. They must therefore obtain the required knowledge from books, monographs, adult education courses, seminars, conferences, and other resources. This situation is not expected to change in the foreseeable future, so a program of continuing education must be maintained.

Experimental Research: Japan and the United States

Developments in earthquake engineering research and practice are based on the hard facts provided by experimental research. In earthquake engineering, experimental research involves the use of shaking machines, shaking tables, structural testing machines, testing machines for structural elements, laboratories for testing large-scale structural models, instruments for recording motions, strains, forces, and pressures, equipment and computing facilities for processing and analyzing data, and other devices. Experimental research is carried out in the laboratory, on actual structures, and by preparing to record data during actual earthquakes.

Japan now has under way an impressive program of experimental research that includes well-equipped laboratories, large earthquake simulation shaking tables, shaking machines, and other equipment. A very large shaking table facility, capable of shaking 1,000 tons at strong earthquake levels, is just being completed at a capital cost of about $200 million and with an estimated operating cost of $1 million per month. This facility can test a full-scale nuclear reactor and containment vessel plus appurtenances under realistic levels of earthquake shaking.

The Japanese program of earthquake engineering research, excluding the large experimental facilities, is four to five times greater than the U.S. effort, and the program is notably stronger in experimental research. An important motivation for this strong research effort is the awareness in Japan of the probability of an earthquake disaster.

There is a strong need for strengthening the United States' weak experimental research program in earthquake engineering. University research and teaching laboratories should be improved with modern instrumentation and equipment. More and better facilities should be available for experiments on structural components and large-scale models, and adequate facilities should be available for realistic testing of actual structures. Workshops, conferences, and an evaluation committee should address the needs of experimental research. A U.S. national program should then be drawn up and specific recommendations made.

General Conclusion

Earthquake risk is significant for much of the United States and should be considered as part of the environment in planning and designing facilities and structures. The U.S. investment in construction is at a rate of $230 billion per year, with better than half of that in seismic regions. The cumulative investment is measured in trillions of dollars, and it is this that is at risk. The present U.S. effort in earthquake hazard reduction is inadequate to solve the earthquake problem in the foreseeable future, that is, to make cities, industries, and military facilities safe against earthquakes.

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

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*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

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*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.

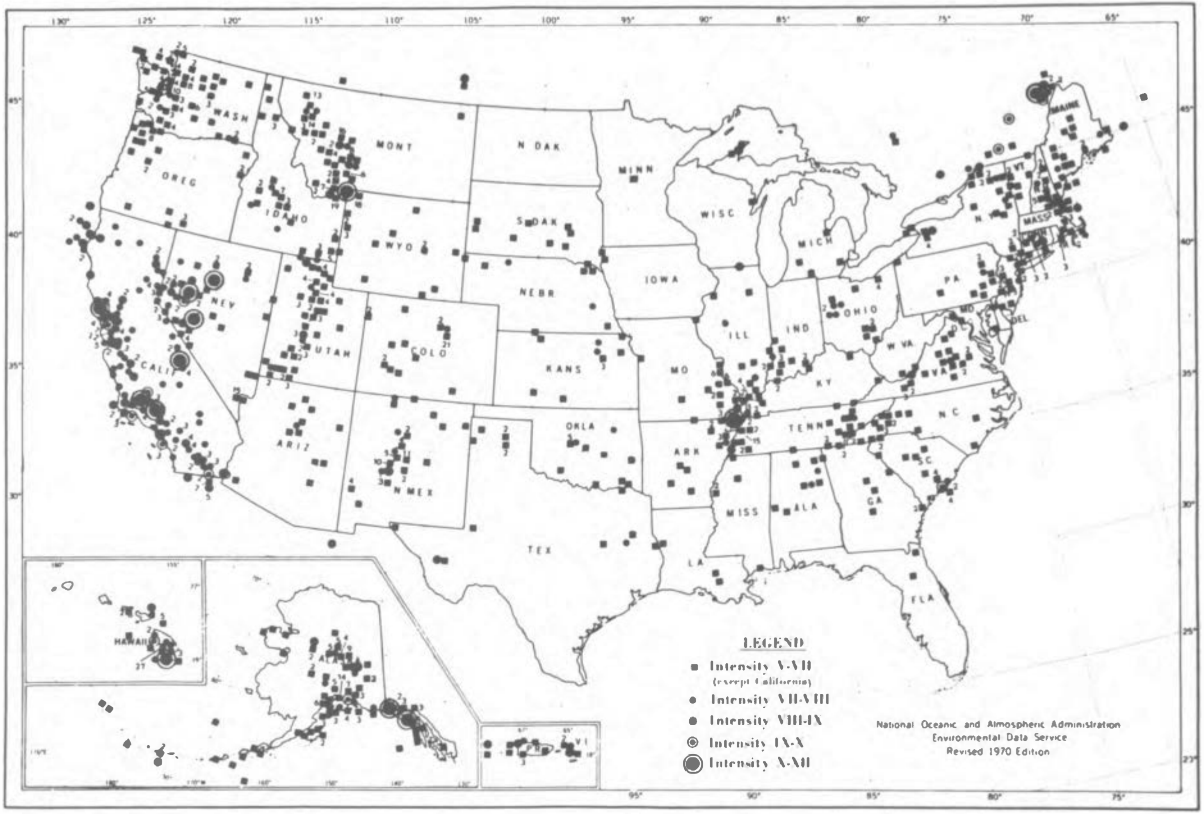
Recommendations

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.

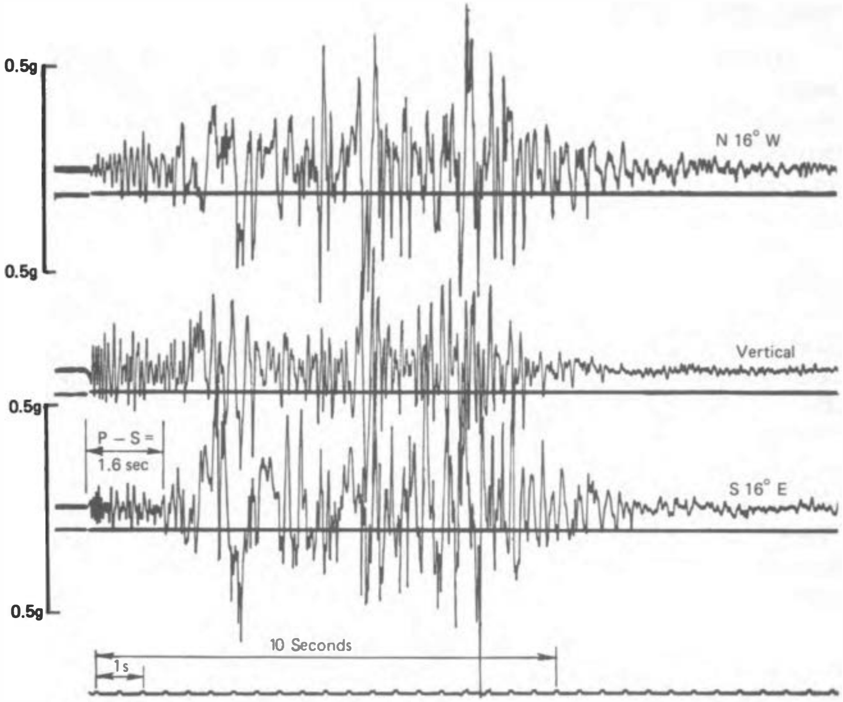
Recording and Analyzing Earthquake Ground Motions

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

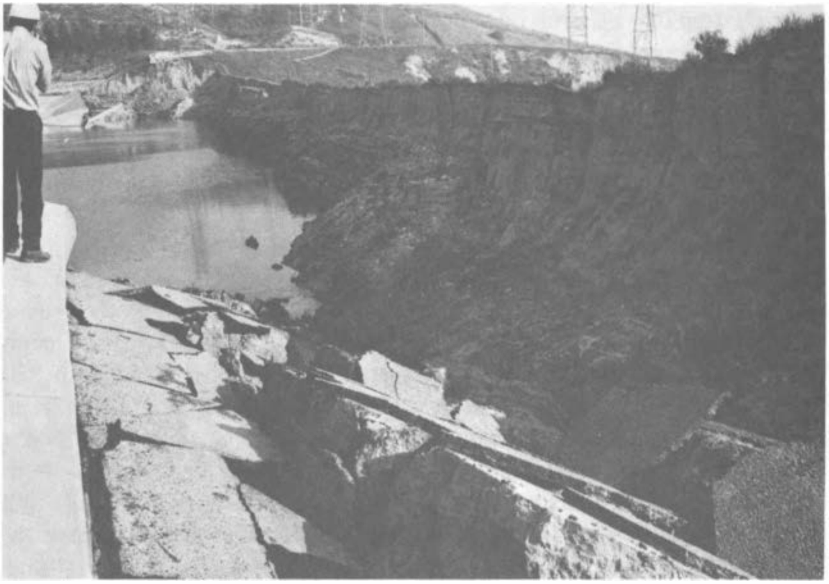
1. A strong effort should be made to record destructive ground shaking of future earthquakes. Better methods of forecasting these motions should be developed, and careful assessments should be made of seismic probabilities. Appropriate instrument networks or arrays should then be installed to record 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

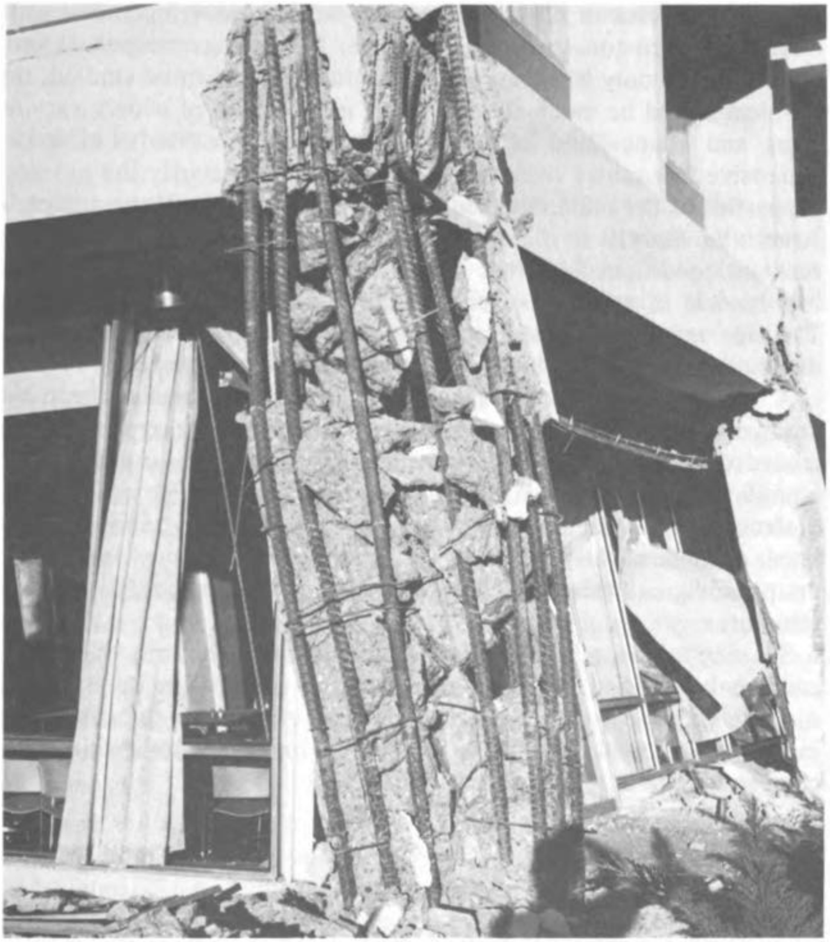
1. The performance during earthquakes of soils and soil structures and soil-structure interaction should be studied by measuring and recording displacements, deformations, and stresses under conditions like those produced by earthquakes. These studies should include both experimental laboratory tests 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.

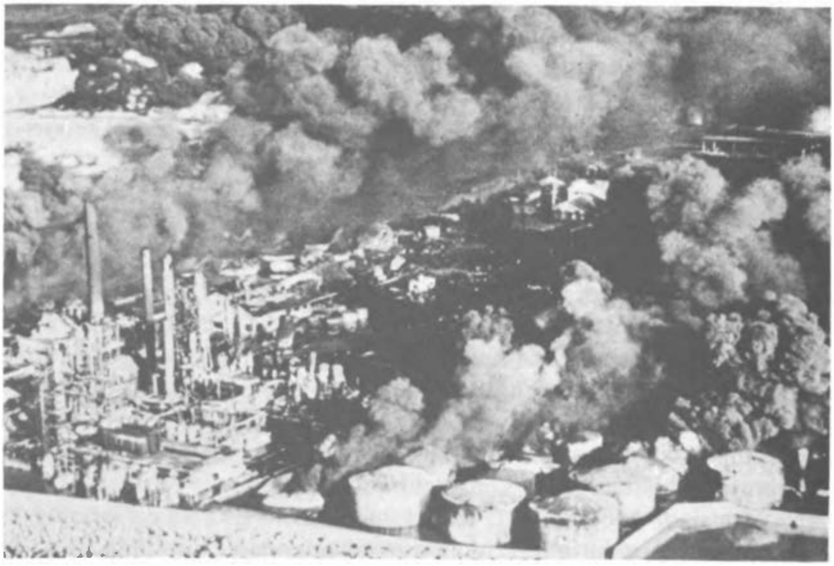
During an earthquake the motion of the ground moves a dam against the water in the reservoir, generating water pressures against the face of the dam. In addition, the vibrations of the dam induced by the earthquake interact with the water, producing additional dynamic fluid pressures. In recent years 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.

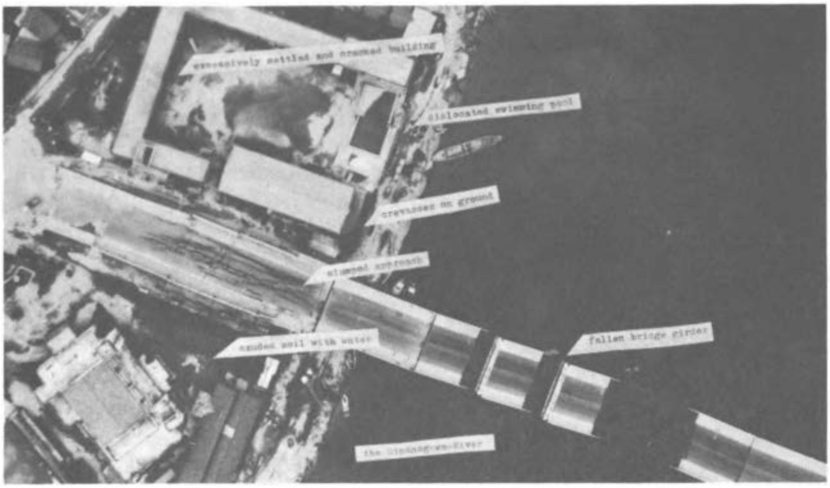
A number of societies and organizations play important roles in earthquake engineering. These include the Universities Council for Earthquake Engineering Research (UCEER), the Earthquake Engineering Research Institute, the Seismological Society of America (SSA), the Applied Technology Council (ATC), 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.

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*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.

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.

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