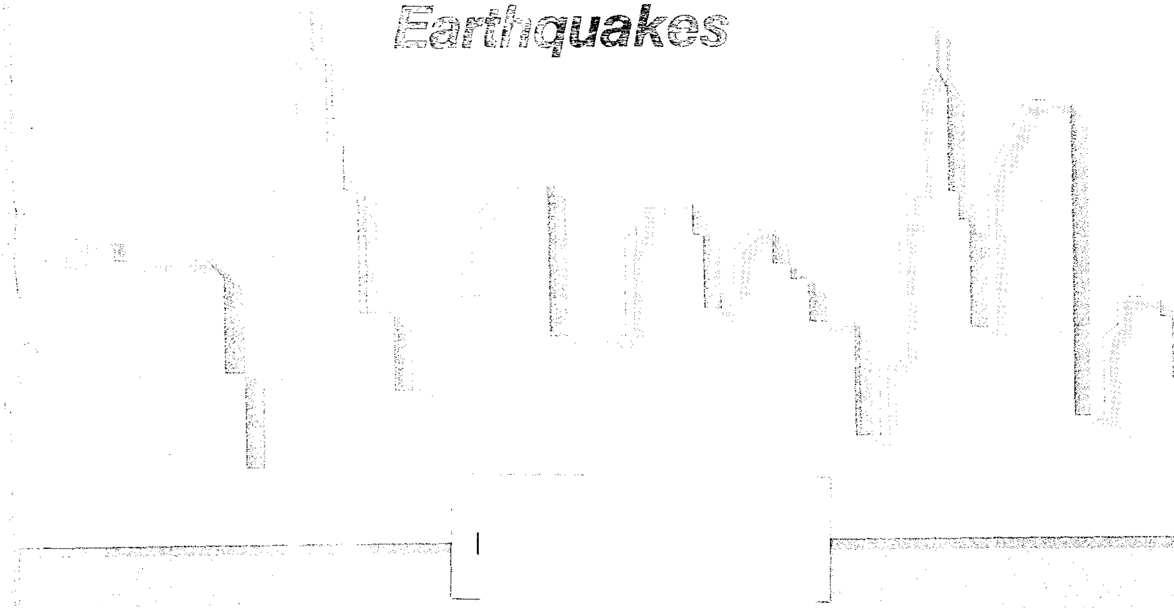
STRONG-MOTION ENGINEERING

The Key to Understanding and Reducing the Damaging Effects of Earthquakes



NATIONAL ACADEMY OF SCIENCES

STRONG-MOTION ENGINEERING SEISMOLOGY:

The Key to Understanding and Reducing the Damaging Effects of Earthquakes

Panel on Strong-Motion Seismology,
Committee on Seismology,
DIVISION OF EARTH SCIENCES
NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1973

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Preface

Increasing numbers of lives are endangered and substantial economic resources are jeopardized by the growing urban expansion in earthquake-prone areas. This expansion will probably continue for many years. An important factor that complicates any earthquake-hazard-reduction program is that seismologists, geologists, and engineers still know far too little about quantifying the various kinds and degrees of earthquake hazard.

We can mitigate undesirable earthquake effects in a number of ways, but not all are currently feasible. Techniques are being developed with which land-use planners will be able to zone, as geologically hazardous, active-fault areas, potential landslide areas, and regions of structurally poor ground. The role of the earthquake engineer is then to reduce the hazards to acceptable levels wherever possible. However, the vast majority of the population of earthquake-prone regions, as well as most developed property, are located not directly in fault zones and landslide areas but in areas where strong ground shaking can cause loss of life and property damage. It follows, then, that the key to an efficient hazard-reduction program is an adequate understanding of the destructive seismic forces involved—or, in other words, of the characteristics of the strong ground motions of earthquakes. The earthquake at Managua, Nicaragua, on December 23, 1972, is a recent example of a moderate earthquake (M = 6.2) that caused extensive destruction directly related to local strong ground motion.

Many groups have attempted to develop a better understanding of earthquakes and their effects, including strong ground motion, but when the Committee on Seismology reviewed the seismological programs currently under way in federal agencies, it found significant inadequacies. Because the emphasis on strong-motion seismology is changing, as well as institutional responsibilities for its conduct and support, the present appears to be a critical time to develop recommendations that will help formulate future directions for this very important program. For these reasons, the Panel on Strong-Motion Seismology was formed to determine whether the needs of the nation are being met by current work and by the present state of the art of strong-motion seismology.

The Panel has developed the four recommendations presented in this report. The first recommendation is concerned with the geographic distribution of strong-motion instruments and the immediate requirement for a substantial increase in the number of instruments. Recommendations 2 and 3 encompass an integrated approach ranging from the extremes of pure research to applications with short-term payoffs. It is important to note that these recommendations are concerned with concurrent efforts as well as with a method that will allow the results of pure research to be applied in the quickest possible manner. The fourth recommendation calls for funding of $4 million a year to establish and maintain the new program over the next five years.

KARL V. STEINBRUGGE, *Chairman*
Panel on Strong-Motion Seismology

Acknowledgments

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The Panel is also grateful to the National Oceanic and Atmospheric Administration, the Bureau of the Census, and the Atomic Energy Commission for help with the illustration.

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xii

Summary of Recommendations

The Panel on Strong-Motion Seismology believes that an accelerated program must be instituted immediately. It is needed to provide the strong-motion information required for engineering purposes, improved handling and utilization of data, and at the same time, an improved understanding of earthquake source mechanisms.

The Panel recommends the following:

1. An increase of 2,000 strong-motion instrument stations in the United States, at least one fourth of them to be emplaced east of the Rocky Mountains.
2. A carefully planned strong-motion program that will include efficient distribution of instruments, improved gathering and processing of data, and improved education in the use and application of data.
3. Immediate intensification of research into the causes and mechanisms of earthquakes.
4. Funding of about $20 million to establish and maintain the recommended program over the next 5 years.

Introduction

Strong-motion seismology is concerned with the measurement of the amplitude-time history of seismic waves in the proximity of the source of an earthquake, where they are strong enough to be hazardous to life and damaging to man-made structures. The hazardous effects of motions caused by earthquakes result from a combination of factors, of which ground acceleration and duration are especially important. For this reason, strong-motion seismographs are designed primarily to record acceleration as a function of time and are therefore frequently called accelerographs.

The teleseismic instruments in the 300 seismographic observatories around the world record seismic waves generated by distant earthquakes. These instruments are much more sensitive than accelerographs and have different recording characteristics. Strong-motion seismographs, however, are used to record the ground motions in the near-source regions of earthquakes, which are of primary importance for engineering purposes. Knowledge of the key elements of strong ground motion—displacement, velocity, acceleration, and duration—is essential to the development of earthquake-resistant engineering design and is an important factor in understanding basic seismological phenomena such as the focal mechanisms of earthquakes.

Probably no part of the world has a denser network of strong-motion instruments than the Los Angeles area. Yet, even here, the distribution of instruments was inadequate to provide records of the motions of the San Fernando earthquake of February 9, 1971, in many of the major damage areas. Clearly, more and better-placed instrument stations are needed to enable scientists and engineers to extract the key information from the observed performance of buildings and other structures. In less-well-instrumented areas, it may be virtually impossible to interpret structural performance.

In 1964, no strong-motion instruments were in operation anywhere in Alaska when it was struck by one of the strongest earthquakes known to have occurred on the North American continent. Approximately 50 recently installed accelerographs are now operating in the entire eastern United States (R. B. Matthiesen, June 1973, personal communication), despite the fact that no state is completely immune to earthquake hazard (282 earthquakes were felt in 22 states in 1972). Moreover, applying strong-motion information from one region to the conditions in another is of debatable validity without a fuller understanding of the major factors involved (source mechanisms, transmission of energy, and geological effects). Thus, design of structures in cities such as Charleston, South Carolina; Buffalo, New York; Boston, Massachusetts; and St. Louis, Missouri, based on information obtained from such events as the San Fernando earthquake near Los Angeles, California, and the 1940 El Centro earthquake in the Imperial Valley of California, involves many uncertainties.

No strong-motion data are available for earthquake sources east of the Mississippi. An accelerogram of even a moderate earthquake would be of great value. If the necessary information is to be made available to guide structural engineers and public officials in their efforts to safeguard millions of people, then the need for developing and expanding strong-motion seismology must be more widely recognized.

There is good reason to believe that, with concerted effort, major advances toward decreasing the earthquake hazard in all regions can now be made. Recent analytical and technological advances offer tangible opportunities for major gains in nearly every aspect of earthquake-hazard reduction. Important advances in the understanding of seismic-source mechanisms, transmission of energy from the source region, effect of local geology on vibrations, and the dynamics of structural response are all possible with appropriate facilities and adequate study.

As an example of the delay in the growth of scientific knowledge that has resulted from the inadequacy of the distribution of strong-motion instruments, the accepted values of maximum accelerations believed to have been reached during earthquakes have increased with increasing instrument coverage of ground motion over the past 30 years as follows:

1940–1966	Maximum believed to be about 0.31 *g** (El Centro earthquake)

**g* is defined as acceleration equal to one gravity unit or 980 cm/s^2.

1966–1971	Maximum believed to be about 0.5 *g* (Parkfield earthquake)
1971–present	Maximum believed to be as high as 0.7–1.2 *g* (San Fernando earthquake)

The increased number of instrument stations has made possible this improved understanding of ground acceleration and thereby created greater awareness of the potentially destructive forces that must be considered in design. It is expected that the use of more instruments will allow other critical information about earthquake effects to be recognized without undue time delays.

Response to Recommendations of Earlier Study Groups

Several highly competent groups have previously made recommendations for updating seismological instrumentation and for improving the deployment of instruments. They have also recommended basic studies of the effects of local geology on vibrations, basic studies of source mechanisms and propagation paths, revised analytical procedures, and better dissemination of the data. Little is to be gained by restating their accepted conclusions. It is time, however, to take stock of actions that have resulted from recommendations made in the following earlier reports:

Earthquake Prediction: A Proposal for a Ten-Year Program of Research. A report of the *Ad Hoc* Panel on Earthquake Prediction to the Office of Science and Technology, 1965.

Earthquake Engineering Research. A report to the National Science Foundation, prepared by the NAE-NRC Committee on Earthquake Engineering Research, 1969.

Seismology: Responsibilities and Requirements of a Growing Science: Part I, Summary and Recommendations; Part II, Problems and Prospects. A report of the NAS-NRC Committee on Seismology, 1969.

Report of the Task Force on Earthquake Hazard Reduction. A report to the Executive Office of the President, Office of Science and Technology, 1970.

Inquiries directed to the appropriate federal agencies show that adequate action has not been taken on most of these recommendations. Only small-scale efforts, including small grants, have been made in improving the design and construction of new strong-motion instruments. Some work on packaging of instruments and on down-hole instrumentation is currently in progress. The Veterans' Administration is in the process of installing about 100 strong-motion instruments, one at each of their facilities located in seismic zones 2 and 3—areas where stronger earthquakes have occurred in the past. In California, some limited studies using strong-motion instruments are being conducted on source mechanisms, near-source transmission of seismic waves, and the effects of local geology and topography on vibrations.* In general, however, the deployment of strong-motion instruments in areas other than California is proceeding too slowly.

*In 1971, the California State Legislature passed the Strong-Motion Instrumentation Program Act. The resulting program is administered by the California Division of Mines and Geology and supported by construction fees collected by cities and counties. The Act provides that strong-motion instruments will be placed in geographic areas not yet covered, in representative buildings and structures, and on representative soil and rock sites throughout the state.

Recommendations

Because of the importance of strong-motion seismology in providing the basic information needed to mitigate earthquake effects, the Committee on Seismology assigned to the Panel on Strong-Motion Seismology the responsibility of reviewing the status of the field. The Panel presents its findings in the following recommendations and discussions.

1 Number and Distribution of Strong-Motion Stations

The Panel recommends an immediate increase in the number of strong-motion instrument stations in the United States by approximately 2,000, with at least 500 of the new stations installed east of the Rocky Mountains.

The strong-motion data currently available for western United States earthquakes are, at best, scanty, and we know of no strong-motion data for eastern earthquakes. A desirable distribution of strong-motion seismic instrument stations would permit every damaging earthquake in the United States to be recorded at one or more instrument stations, making it possible to scale the event with some accuracy rather than relying on speculation. Furthermore, at specified locations (such as Los Angeles, San Francisco, Seattle, Salt Lake City, Charleston, and the New Madrid area) the density of station coverage should be sufficient to ensure that records are obtained within 10 km of future earthquake sources to provide critical information about close-in ground motion. The inadequacy of the current data bank is illustrated by Table 1, which gives the numbers of all strong-motion records accumulated in the last 40 years for earthquakes in the United States. There is a clear need for a major increase in the number of instrument

TABLE 1 Strong-Motion Records vs Distance from the Fault for U.S. Earthquakes During the Past 40 Years[a]

Distance (km)	Numbers of Records
0	1
0–5	1
5–10	8
10–20	11
20–40	52
40–60	33
60–80	25
80–100	7
100–150	19
150–200	6
200–300	50
300–400	12

[a]Data provided by the Earthquake Engineering Research Laboratory, California Institute of Technology.

stations to provide the data essential for engineering and scientific purposes.

Strong-motion instruments are designed to record the violent shaking of destructive or damaging earthquakes at or near their sources. The Committee defines a strong-motion instrument station* as an installation including one or more strong-motion instruments in a single structure or in adjacent structures. It is estimated that 600 to 800 such stations exist at this time, mainly in California. Of the 2,000 additional instrument stations recommended, 1,500 stations are to be distributed west of the Front Range of the Rocky Mountains, taking into consideration the current strong-motion instrument programs in California. It is recommended that 500 stations be installed east of the Rocky Mountains, where about 50 moderate earthquakes and at least two major earthquakes have occurred in historic time. Particular attention

*Most seismograph stations contain only sensitive instruments, designed to record distant earthquakes to provide information on source mechanisms and the character of the earth's interior. These instruments are much too sensitive to record the violent shaking in or near the epicentral regions of damaging or destructive earthquakes, because they are promptly driven off scale when strong ground motions occur.

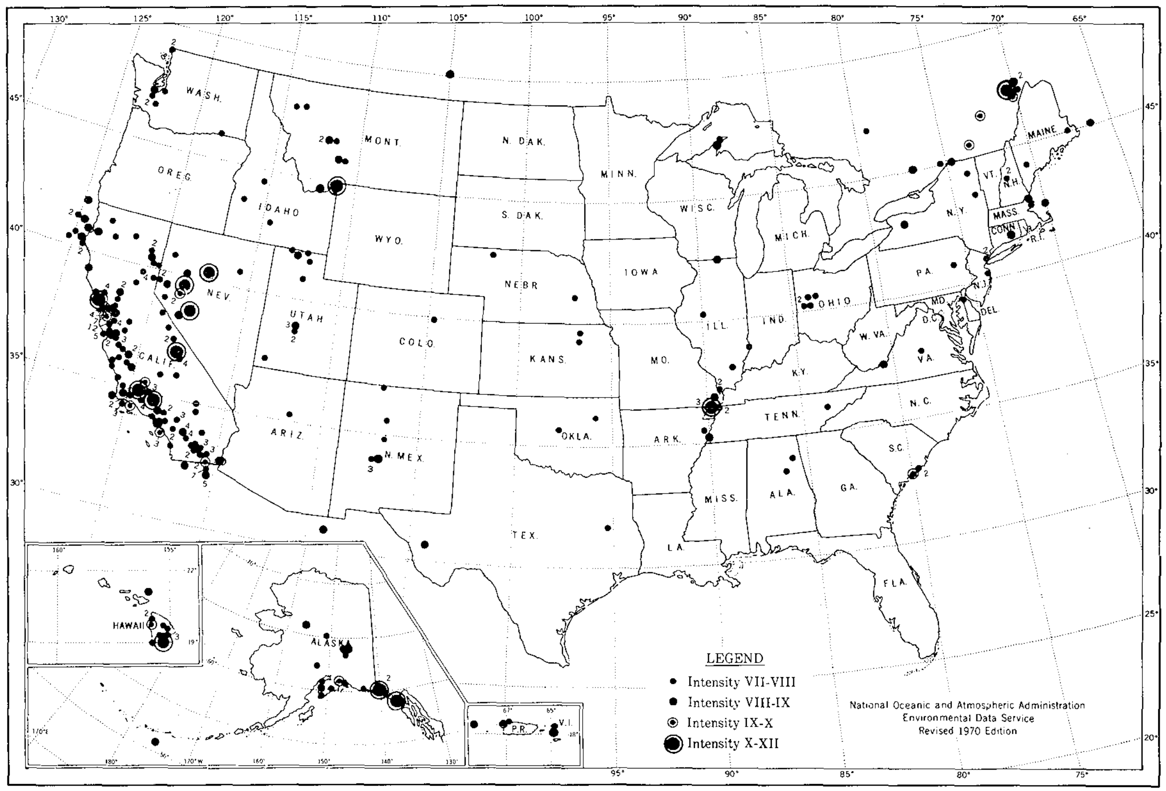


FIGURE 1 Intensity and location of damaging earthquakes in the United States from earliest history through 1970. (Intensity is a measure of local damage.)

should be given to the more seismically active areas in the east, with commensurately more stations in the states of Arkansas, Missouri, Illinois, Tennessee, Kentucky, Ohio, New York, Mississippi, and South Carolina.

It is by no means certain that strong-motion records obtained from large shocks in California can be used to represent adequately the shaking that would be produced by large earthquakes occurring in the east. The spectra (amplitude and frequency data) are likely to be significantly different. There are no existing data for earthquakes in the east, and it is essential, therefore, that measurements be made there now.

Figure 1 shows the intensities and locations of damaging earthquakes in the United States from the earliest on record through 1970. Figure 2 shows the present locations of strong-motion instruments in the United States. Figure 3 shows the population distribution of the United States. Figure 4 shows the locations by state of nuclear power plants, both those operable or being built and those planned (reactors ordered). The greater seismicity of the western United States is evident from Figure 1. However, the seismicity of portions of the eastern United States is significant, and because of population density and the distribution of such features as nuclear power plants, refineries, dams, and high-rise buildings, all of which must be constructed with particular consciousness of earthquake hazards, many additional strong-motion instruments must be deployed in the eastern United States to collect invaluable and vitally needed strong-motion data.

An increase in the number of stations such as that proposed would undoubtedly inspire the development of more efficient instruments, but the strong-motion seismographs already developed are capable of obtaining the kinds of information needed. The installation program should therefore proceed immediately with currently available equipment.

The continuing operation of a strong-motion network such as that proposed would repay the nation many fold in the years to come, particularly as population continues to move into larger concentrations that are more vulnerable to the devastation of large earthquakes. The recommended increase in stations would provide for the minimum number of instrument stations required to help evaluate structural design and aid in planning for future development in all parts of the United States.

2 Planning the Strong-Motion Program

The Panel recommends that the strong-motion program be carefully planned so as to optimize its usefulness and effectiveness in all parts

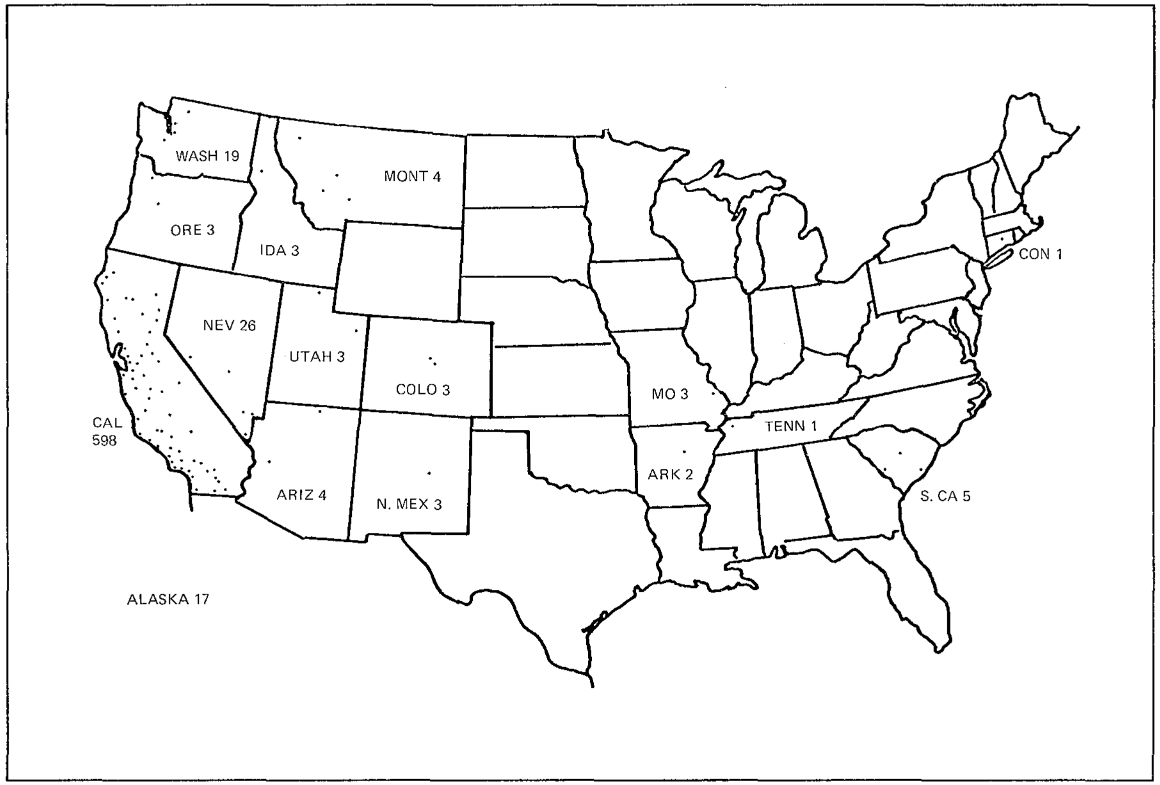


FIGURE 2 **Locations of 695 strong-motion accelerographs in the United States in 1972.**

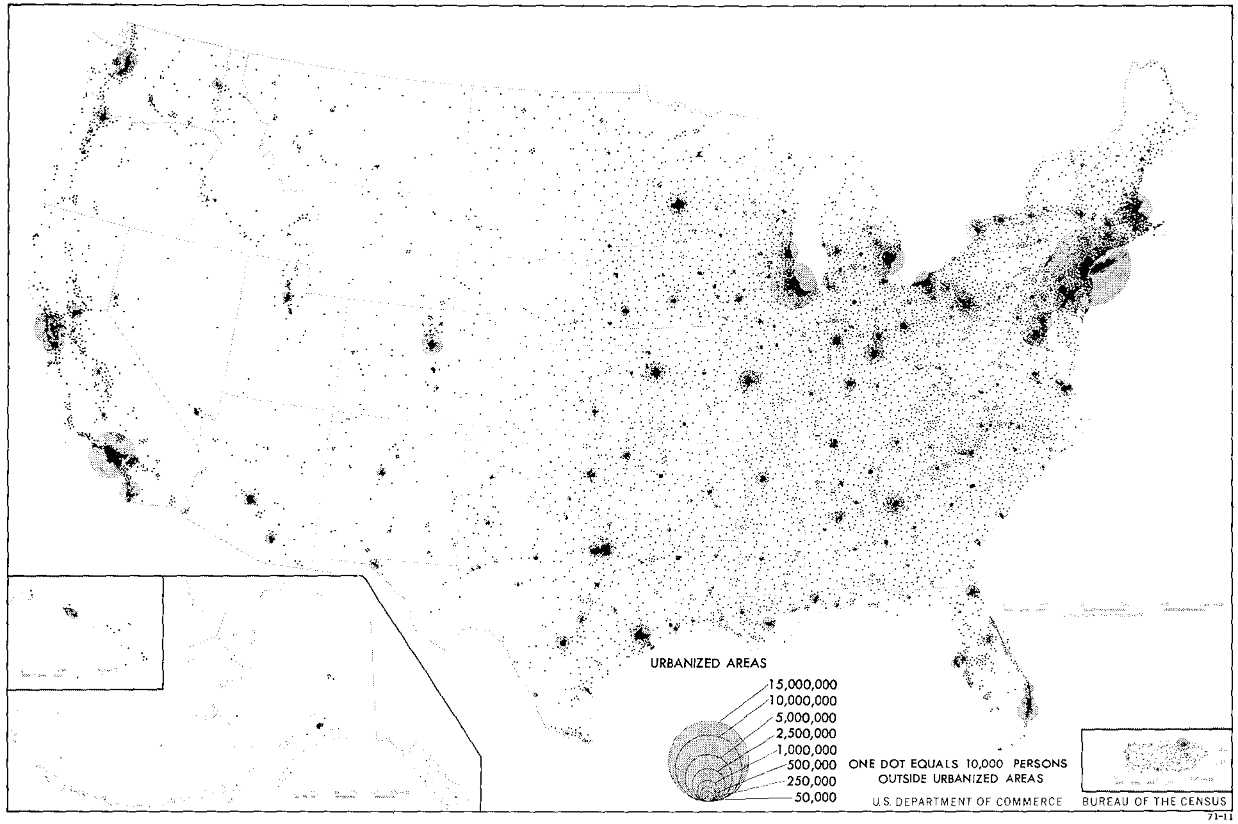
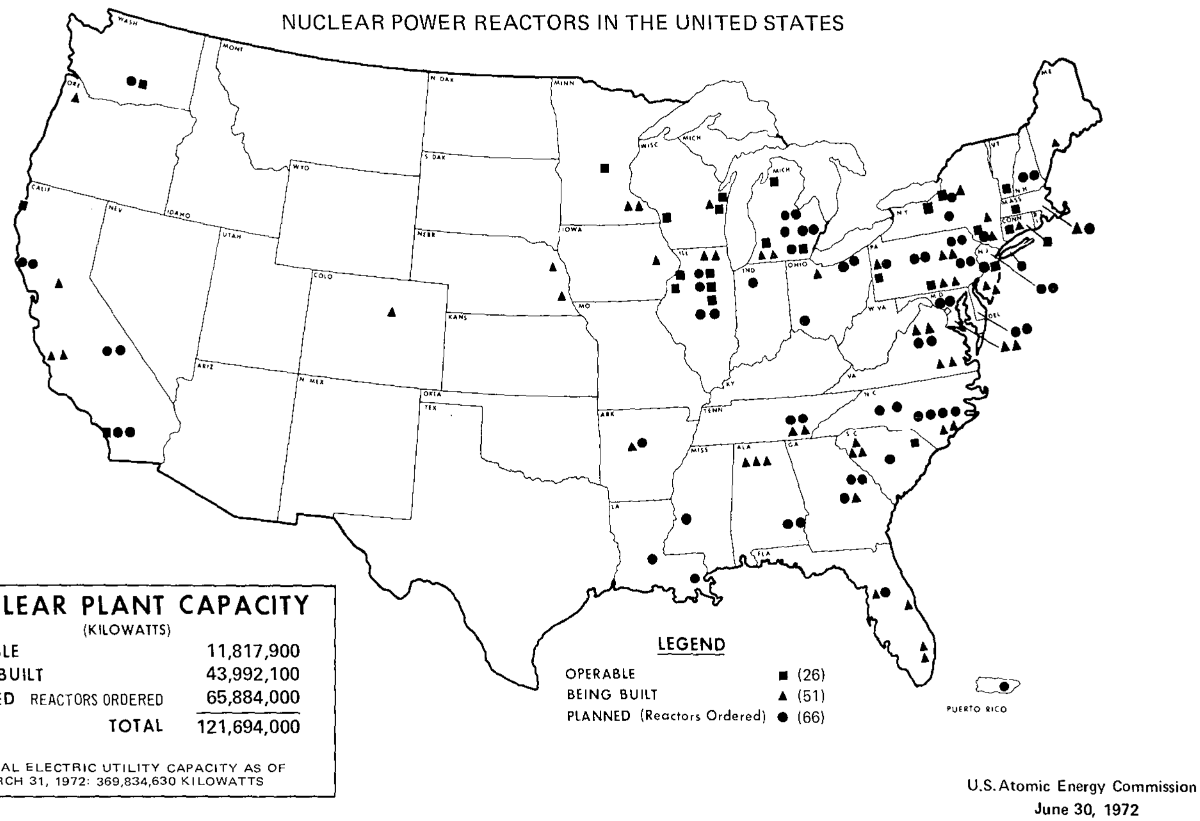


FIGURE 3 Population distribution of the United States, 1970.



NUCLEAR PLANT CAPACITY
(KILOWATTS)

OPERABLE	11,817,900
BEING BUILT	43,992,100
PLANNED REACTORS ORDERED	65,884,000
TOTAL	121,694,000

TOTAL ELECTRIC UTILITY CAPACITY AS OF MARCH 31, 1972: 369,834,630 KILOWATTS

FIGURE 4 Nuclear power reactors in the United States.

of the country. A truly effective strong-motion program requires efficient distribution of instruments, better means of gathering and processing data, and better methods of education in the use and application of these data.

Careful planning of the strong-motion network and augmentation by development programs designed for the most effective use of the data obtained will more than repay the costs, and the survival of structures designed to resist earthquakes will be more certain if these programs are put into effect. Every earthquake that occurs in a populated region re-emphasizes the inadequacies of our preparations for such disasters as well as the need to improve our ability to predict the zone of earthquake damage and to make more informed and more accurate estimates of earthquake effects in urban areas. (The moderate San Fernando earthquake, on the fringe of a major high-density population center, caused damage estimated as high as $1 billion.) Attention should be directed specifically to the following aspects of the problem.

Although some strong-motion data are available on which to base engineering studies for earthquake-resistant design, the information is incomplete and covers only a limited range of conditions. Strong-motion seismologists and engineers need a distribution of stations that will provide data for a wide range of earthquake magnitudes, distances from source of energy release, geological conditions, and depths below ground surface. Little information is available, for example, concerning the influence of depth of foundation materials on the ground motion transmitted to a structure, or concerning the influence of structure–foundation interaction on motions in the vicinity of a structure. Consequently, even while new strong-motion stations are being installed, the locations of future stations should be carefully selected to extend the potential engineering usefulness and effectiveness of the instruments deployed and of the records that will be obtained. When appropriate, the planning for new stations should include the locations of future earthquakes as identified by prediction methods that are currently being developed.

To make strong-motion data more useful, the processing of strong-motion records and their distribution to all workers in the field must be speeded up and improved. Because of the expected increase in the amount of data that will be developed, the processing methods used in the past will no longer be adequate or satisfactory. Automation in data handling and interpretation is essential if we are to benefit fully and expeditiously from the increased amounts of empirical data obtained from actual earthquakes. Moreover, data-handling processes should be compatible, through use of international standards when they are available, in order to permit interchange of information from one country, or one geographic region, to another.

Specialists at research institutions are currently working on the application of strong-motion data to earthquake-resistant design, but the training of architects, engineers, and planners should include increased emphasis on this subject so that the work done in research can be put into practice immediately and directly, Short courses, texts, tutorial sessions, and other methods should be used to instruct the users of strong-motion data in efficient methods of applying the results of research.

Appropriate government agencies should be assigned the responsibility for the management of the various aspects of the program, such as (a) planning and optimization of instrument placement, (b) processing and distribution of records, and (c) applications to practice.

3 Intensification of Earthquake Research

To support and supplement the program in recommendations 1 and 2, the Panel recommends immediate intensification of research into the causes and mechanisms of earthquakes.

Perhaps one of the least-understood aspects of an earthquake is the mechanism operating at its source. What are the differences among earthquakes in different geological regions? How much stress is required to rupture the rocks at a particular location, and how much is necessary to overcome friction? At what velocities do these crustal ruptures propagate and over what distances? These and other pertinent questions must be answered before an acceptable model of an earthquake can be constructed. The deployment of instruments and the collection of data are essential elements in achieving the goal of mitigation of earthquake effects, but these efforts must be supported by an expanded program of research into the causes and mechanisms of earthquakes.

At best, our sampling of earthquakes in time and space is sparse. It is necessary, therefore, to make use of models to the fullest extent possible in order to study earthquake mechanisms and to develop methods for predicting the general nature of strong ground motion at a given site. Although major advances have been made in the analysis of earthquake mechanisms, a theory acceptable to most seismologists has not yet been developed. The present inadequacies stem from the complexity of the phenomena, the lack of strong-motion data, and the absence of adequate modeling or simulation of earthquake source and propagation mechanisms. Hence, research is needed to develop concepts for instrument deployment that will yield data that can be used to evaluate hypotheses concerning earthquake mechanisms and that will lead eventually to improved understanding of seismic phenomena in general.

To develop models that will be of maximum usefulness, it is essential to document near-source strong motions, in particular, by increased deployment of instruments around active faults. Unfortunately, the distribution of instruments in the past has generally not been carried out with this purpose in mind.

More detailed studies should be made of the effects of the geologic structure in the region between the source and the damage site, of surface topography and local soils effects, and of the interaction between soils and geologic structure. These and related investigations will help to characterize the similarities and differences between earthquakes in the eastern and in the western United States, in general, and among tectonically different regions or provinces, in particular, so that knowledge gained in one region can be used or applied in another. In addition, the Panel urges that near-source seismological studies be conducted in other countries where earthquakes occur more frequently than they do in most parts of the United States, especially when there is a reasonable likelihood that the knowledge gained will be transferable.

4 Funding Requirements for the Program

The Panel believes that to implement recommendations 1, 2, and 3, approximately $20 million will be needed over the next five years; the Panel recommends that this amount be made available to the appropriate federal agencies.

A considerable proportion of these funds will have to be used to install and maintain the new stations proposed in recommendation 1; however, it is equally important that the planning discussed in recommentation 2 and the supporting research on source mechanisms of earthquakes proposed in recommendation 3 also be adequately funded to assure the maximum benefit from the overall program.

The amount of support recommended for this program is small compared with the cost of a moderate earthquake near or in a great metropolis, or a major earthquake in a sparsely populated area. The damage caused by the moderate San Fernando earthquake of February 1971 was estimated between $0.5 and $1 billion, and there were 64 deaths; the damage caused by the great Alaska earthquake of 1964 was over $300 million, and there were 115 deaths. It has been estimated, moreover, that if an earthquake similar to the 1906 earthquake occurred today in San Francisco, damage would be measured in billions of dollars and deaths in the thousands.

With billions of dollars being spent each year in construction, a worthy national goal would be to ensure the integrity of future structures in all earthquake-prone areas and to require standards for essential public-use structures already in existence. Even so, it is necessary to have sufficient and appropriate data to prevent excessive construction costs that could result from overdesign. We have been taught by previous earthquakes that we must be better prepared—but have we really learned the lesson? The recommended additional $4 million per year may help to answer that question.

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A comprehensive bibliography on strong-motion seismology can be obtained, on request, from the Division of Earth Sciences, National Research Council, 2101 Constitution Avenue, Washington, D.C. 20418.