Recommendations for the Strong-Motion Program in the United States

Panel on Strong-Motion Instrumentation
Committee on Earthquake Engineering
Commission on Engineering and Technical Systems
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1987

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This study was supported by the National Science Foundation under Contract No. CEE 8418379 to the National Academy of Sciences. Any opinions, findings, and conclusions or recommendations expressed in this report are those of the committee and do not necessarily reflect the views of the National Science Foundation.

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OVERVIEW AND RECOMMENDATIONS

The fundamental objective of the National Earthquake Hazard Reduction program is to develop economically and socially acceptable methods for minimizing damage caused by earthquakes. Injury, loss of life, and loss of property most commonly are caused by the failure of man-made structures or facilities due to strong ground shaking.

The design of safe and economical engineering structures requires an understanding of the nature of earthquake ground motion and the response of the structures to it. An adequate understanding can only be attained by instrument measurement of the physical processes involved; that is, by actually measuring the motion of the ground and base of the structure as well as the vibratory response of the structure during an earthquake. Such strong-motion instruments play a crucial role in providing data for earthquake hazard mitigation.

Previously recorded strong-motion data have greatly enhanced knowledge about the fault rupture process, the transmission of seismic wave energy from source to site, and the dynamics of structures, although the data base is far from comprehensive. There is a need not only for more data but also for more sophisticated types of data and analysis. Also, to be useful, the information must be made available in a timely manner to the many engineers and scientists who require it for design, analysis, and research. Data management and distribution are becoming increasingly important as the number of strong-motion instruments and organizations that deploy them keeps growing. The totality of those involved in obtaining strong-motion records, processing, archiving, disseminating, and using strong-motion data is called, for purposes of this report, the U.S. Strong-Motion Program.

To accommodate the increasing and changing needs in strong-motion instrumentation, which include the acquisition, processing, archiving, and dissemination of the data, and in view of changing research needs, the Panel on Strong-Motion Instrumentation makes the following six recommendations.

1. The Committee on Earthquake Engineering and the Committee on Seismology of the National Research Council should establish a continuing Joint Subcommittee on the U.S. Strong-Motion Program. This subcommittee would develop and submit a general plan for the U.S. Strong-Motion Program, submit periodic (annual or biannual) updates of the plan, and submit a yearly report on the program's status. Before undertaking this activity, the subcommittee should organize a workshop or conference for users and beneficiaries of strong-motion data. The proceedings of such a meeting could be used to help develop the initial plan, which would provide recommendations for tasks to be undertaken during a five-year period. The plan should be developed in consultation with and participation by relevant public and private agencies and organizations. It should include at least the following elements:

- Guidelines for integration and coordination of federal, state, university, and private U.S. strong-motion activities,
- Guidelines for archiving and disseminating data,
- Recommendations for data processing and data format standards,
- Strong-motion research needs and priorities,
- Strategy for application of research results,
- Funding needs and priorities,
- Instrument development and performance guidelines, and
- Instrument deployment strategy.

2. A strong-motion data center, or centers, should be established. The center(s) should compile a catalog of strong-motion data parameters (1933 to the present), publish annual updates of the strong-motion catalog, promptly disseminate raw and processed data upon request, archive strong-motion data in a standard format, and ininclude data from U.S. government sponsored strong-motion data acquisition projects in foreign countries as well as

in the United States. This may require expanding the strong-motion operations of the National Geophysical Data Center (NGDC) and/or establishing other data centers. One of the first projects of the joint Subcommittee on the U.S. Strong-Motion Program should be to review the needs for a strong-motion data center, or centers, and to make specific recommendations on the establishment, operation, and guidance of the center(s). A possible role model is the U.S. Geological Survey's facility in Golden, Colorado, which expeditiously provides copies of analog and digital observatory seismograph data at low costs to all who request them.

3. <u>The Science Directorate of the National Science Foundation should consider the funding of research proposals in seismology that would enhance the capability of strong-ground motion estimation.</u> This activity should be coordinated with the strong-motion activities of the Engineering Directorate of the National Science Foundation and the U.S. Geological Survey. The Engineering Directorate of the National Science Foundation should continue its strong interest in the development and support of strong-motion instrument arrays and networks for engineering purposes. Close cooperation should be encouraged between strong-motion seismologists and earthquake engineers.

4. <u>An external strong-motion research program should be established as part of the Engineering Seismology element of the U.S. Geological Survey, by seeking new funding as required by strong-motion research needs.</u> This activity should be coordinated with the earthquake engineering program in the Engineering Directorate of the National Science Foundation and with the geophysics program in the Science Directorate of the National Science Foundation.

5. <u>Steps should be taken for the effective exchange of significant international strong-motion data.</u> Recordings of strong ground shaking and building responses are often made in foreign countries. There is at present no organized method of making such records available to interested persons in the United States, nor is there an organized method of making U.S. data available to researchers in foreign seismic countries. An effective interchange of strong-motion data would be mutually beneficial. Possible models or organizations for doing this

are NOAA's World Geophysical Data Center A in Boulder, Colorado, or an element of the U.S. Geological Survey.

6. Finally, the panel endorses the proposal for an International Decade of Hazard Reduction (IDHR). The panel recommends that one emphasis of the decade be the development of a coordinated international strong-motion activity with unified instrumentation standards, deployment strategies, data processing, archiving, and dissemination. The panel recommends that an international repository be established under IDHR to carry out these activities.

In implementing the above recommendations, highest priority should be given to the first recommendation.

INTRODUCTION

Safeguarding life and property from the destructive effects of earthquakes is a problem of national scope. Although some regions of the United States have relatively low seismicity, damaging earthquakes have historically occurred throughout the country. Four very strong earthquakes were recorded in the midwest and eastern portions of the country--the New Madrid earthquakes of 1811 and 1812 and the Charleston earthquake of 1886 (Figures 1 and 2).

The U.S. population and the production of goods and services continue to become more concentrated geographically, and this increases the potential for catastrophic loss associated with a single large earthquake. It has been estimated that a credible earthquake in some regions of the country could result in the loss of tens of thousands of lives and cost more than $100 billion in property damage and loss of industrial output and productivity (Federal Emergency Management Agency, 1980). Such an occurrence would clearly have a major national impact, regardless of whether it occurs in the western, central, or eastern United States. Examples of such an event are the September 19, 1985 Mexico earthquake (M8.1), which caused some 10,000 deaths and many billions of dollars of property loss, and the 1976 Tangshan, China earthquake (M7.8), which caused several hundred thousand deaths and greater property losses than the Mexico event.

The ultimate goal of an earthquake hazard mitigation program is to devise and implement socially and economically acceptable strategies for minimizing the loss of life and property resulting from earthquakes. To design safe and economical structures and facilities in earthquake-prone regions, it is necessary to understand both the nature of the ground motion that these systems may

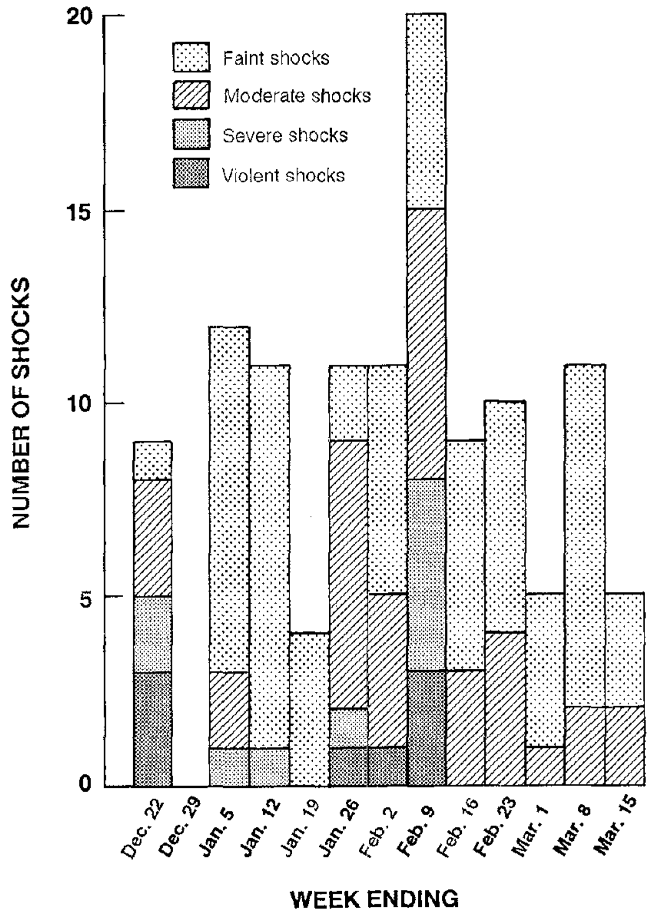

FIGURE 1 A total of 120 shocks were reported as felt in Louisville, Kentucky, approximately 200 miles from the epicenters of the 1811-1812 earthquakes near New Madrid, Missouri. Very strong earthquakes occurred on December 16, January 23, and February 7. Felt at Louisville were 7 violent shocks, 9 severe shocks, 36 moderate shocks, and 68 faint shocks. These earthquakes occurred before seismographs were used and before a significant population existed, but there is no doubt that at least two shocks were of very large magnitude. Source: Fuller (1966).

FIGURE 2 Photograph of building collapse in Charleston, South Carolina. This destructive earthquake occurred August 31, 1886 and caused considerable damage. Its estimated magnitude was 7.7. Source: Dutton (1890).

experience and the nature of their responses to the motions. Much can be learned by computer and mathematical modeling of fault-mechanisms, wave propagation, structural response, soil-structure interaction, and other factors, but a complete and reliable understanding of the phenomena involved can only be obtained from direct measurement of the processes. This requires measurement of near-field strong ground motion and measurement of the response of structures during actual earthquakes.

DEVELOPMENT OF STRONG-MOTION ACTIVITIES IN THE UNITED STATES

The first recording of strong ground acceleration anywhere in the world was obtained during the earthquake of March 10, 1933 in Long Beach, California. In the 1920s John R. Freeman, consulting engineer, and R. R. Martel, professor of structural engineering at the California Institute of Technology, realized that accurate recordings of strong ground shaking were needed to understand the forces exerted on buildings during an earthquake and, also, the measurements of the accelerations of building responses were needed to develop rational methods of seismic design. It was recognized by Kiyogi Suyehiro, professor of engineering at Tokyo University, and by Freeman and Martel that the design of the sensitive Wood-Anderson seismograph pointed the way to the design of a practical strong-motion accelerograph. The Wood-Anderson seismograph was developed in the early 1920s and it had a small torsion pendulum sensor, magnetic damping, and optical recording on a rotating drum (Anderson and Wood, 1925). In the latter 1920s Freeman launched a successful campaign to have accelerographs built and installed in the western United States.

Freeman, an eminent engineer, convinced the then Secretary of Commerce R. P. Lamont and President Herbert Hoover, both engineers, about the need for accelerographs. Secretary Lamont approved the accelerograph project to be carried out by the U.S. Coast and Geodetic Survey in early 1931. Freeman recommended several appropriate instrument characteristics, including a rotating drum for optical recording with a paper speed of about 1 cm/sec and a torsion pendulum with a natural frequency of 10 hertz. The instruments were custom made to the design of the Department of Commerce in 1932, and the first three were installed in three cities in southern California in July 1932: Long Beach, Vernon, and Los Angeles. They were sometimes called "Montana accelerographs." On March 10, 1933 the Long Beach earthquake, having a magnitude of 6.2, was recorded by all three instruments. These recordings had a profound influence on engineering thinking and on earthquake-resistant design in the United States and worldwide (Housner, 1983).

The strong-motion accelerograph network was begun in 1932 and was operated by the Seismological Field Survey of the U.S. Coast and Geodetic Survey. Installation of accelerographs began in July 1932 and continued at a slow pace over the years. The selection of sites for installing the accelerographs was done on the advice of a committee of engineers. By 1964 the network of strong-motion accelerographs had expanded to 71 stations and extended to regions in the western United States outside of California. Computer analysis of the accelerograms and the calculation of response spectra were first carried out in the Engineering Department of the California Institute of Technology (Alford et al., 1951).

In the late 1960s the Seismological Field Survey was merged into the National Oceanic and Atmospheric Administration and operated there until the early 1970s. During the years of the Seismological Field Survey, some very valuable accelerograms were recorded during the following earthquakes: Long Beach, California, 1933; El Centro, California, 1934; Helena, Montana, 1935 (Figure 3); El Centro, California, 1940; Seattle, Washington, 1949; Tehachapi, California, 1952; Olympia, Washington, 1965; and San Fernando, California, 1971.

On February 14, 1965 the City of Los Angeles, at the urging of engineers, passed an ordinance requiring three strong-motion accelerographs to be installed in all buildings more than 10 stories high. By then, accelerographs were commercially available. When the San Fernando earthquake occurred on February 9, 1971, accelerographs in more than 50 buildings recorded strong shaking of ground and buildings (Murphy, 1973).

The strong-motion data provided by this earthquake were many times greater than all the strong-motion data recorded in the world prior to 1971. Gathered were data on the seismic excitations and dynamic motions of buildings of many different heights, shapes, and materials of construction. These had a large impact on engineering analysis and design as well as building codes.

The first commercially available accelerograph in the United States was the AR-240, which was marketed in 1963, followed by the RFT-250, and then in 1970 by the SMA-1.

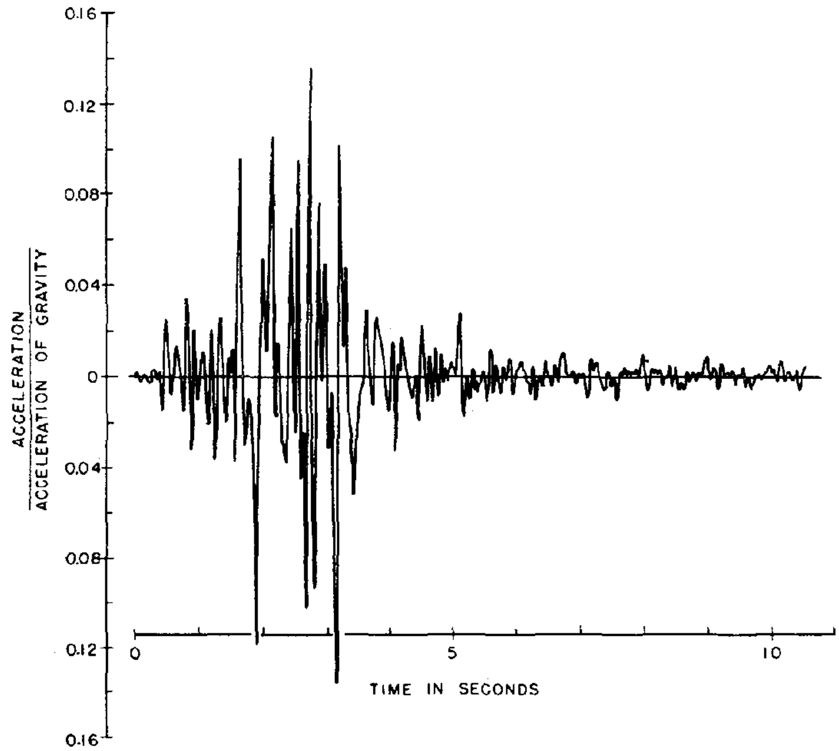

FIGURE 3 North-south component of acceleration recorded during the 1935 Helena, Montana earthquake (M6.0). The duration of strong shaking was 2.5 seconds, as compared to the 4.5 seconds of strong shaking during the Westmorland, California earthquake (Figure 7). The frequency characteristics of the motions also differed. The characteristics of strong ground motions are affected by the nature of the source mechanism, the properties of the earth's crust through which the seismic waves travel, and the local geology at the recording site (Figure 8). (From the California Institute of Technology)

Many federal, state, and local government agencies purchased and installed accelerographs to monitor ground shaking and structural response during earthquakes. Various corporations and organizations, such as public utilities, water departments, and industrial concerns, also obtained accelerographs for special engineering needs.

In addition to engineering information, the ground-motion records obtained during the 1971 San Fernando earthquake also contained information of value to seismologists studying fault mechanism and wave propagation characteristics. Consequently, in the 1970s accelerographs were installed near earthquake faults with the objective of obtaining more information for seismological research. Since then, a number of seismological research programs involving strong-motion instruments have been undertaken, and at present the U.S. Geological Survey (USGS) is planning a strong-motion array near the San Andreas Fault near Parkfield, California as part of a seismological research program on the source mechanism of strong earthquakes.

In the early 1970s, the Seismological Field Survey activities were transferred to the USGS, but funding was provided by the National Science Foundation (NSF). The government decided that the USGS should be responsible for seismological programs and the NSF should be responsible for earthquake engineering programs. Thus, NSF was responsible for the strong-motion accelerograph program but since NSF was not an operating agency the decision was made to attach the Seismological Field Survey to USGS for operating purposes. In the early 1980s, funding in the amount of $1.2 million per year was transferred at agency level from NSF to USGS to provide continuing support for instrumental maintenance and data dissemination, with the understanding that the strong-motion accelerograph program would continue to serve the professional objectives of the engineering community.

STRONG-MOTION ACTIVITIES

A number of special seminars and workshops have been held for the purpose of defining the needs of and setting goals for strong-motion earthquake measurement activity. In May 1978, an International Workshop on Strong-Motion Instrument Arrays was held in Hawaii (Iwan, 1978). The goal of this workshop was to develop a plan for the international deployment of dense strong-motion earthquake instrument arrays. This workshop led to the installation of strong-motion arrays and networks in Japan, China, Taiwan, India, and other seismic regions, some with the support of U.S. federal agencies. However, the workshop had relatively little impact on the deployment of instruments in the United States.

In April 1980, a workshop was held in San Francisco to review strong-motion instrument programs, to document procedures for processing and interpreting data from these programs, and to identify ways to improve data acquisition, analysis, and interpretation techniques for use in the design of engineering structures (Hart et al., 1980). Also in 1980, the Panel on National, Regional, and Local Seismograph Networks drafted a report as the first attempt by the seismological community to rationalize and optimize the distribution of seismograph stations across the United States (Panel on National, Regional, and Local Seismograph Networks, 1980). The panel recommended to incorporate strong-motion sensors in a national network and to maintain a national overview of the distribution and operation of strong-motion seismographs in the United States.

In 1981, a U.S. National Workshop on Strong-Motion Earthquake Instrumentation was convened in Santa Barbara, California. The objectives of this workshop were to review strong-motion instrumentation programs in the United States; to develop a unified strategy for the deployment of strong-motion instruments, both in the free-field and in buildings; and to formulate a plan for coordinating strong-motion programs, the ongoing installation and operation of instruments, and the management of strong-motion data (Iwan, 1981).

The Santa Barbara workshop dealt with many of the technical and management issues facing the U.S. strong-motion instrumentation activity. This workshop provided the stimulus for forming the present Panel on Strong-Motion Instrumentation. The panel report presented herein parallels the workshop proceedings in certain respects, but goes beyond the recommendations of the workshop in both extent and specificity.

The Santa Barbara workshop specifically addressed the need for an overview of the various strong-motion activities in the United States:

> Each of the organizations maintaining strong-motion instruments has its own particular interest in earthquake hazards, and the instruments which they deploy are located to provide informa-

> tion relating to these interests. The effectiveness of these individual programs could be substantially improved through greater cooperation and coordination between the various concerned groups. This includes users as well as organizations involved in data acquisition. Users of strong-motion data should become better acquainted with ongoing strong-motion programs and the availability of data. Conversely, the managers of strong-motion programs should become better acquainted with the needs of the data user.
>
> At present there are many different organizations engaged in the installation and maintenance of strong-motion instrumentation, and in data processing and dissemination of information. A number of these organizations have had long experience in the field, are well-organized, and well-funded and for various administrative reasons would find it impracticable to turn over their basic responsibilities in the subject to any central agency. Therefore, the idea of establishing one central group of any type as the headquarters for a U.S. National Strong-Motion Program would not be a practical approach.
>
> At the same time, it would be a definite advantage if the individual strong-motion programs in the United States could be viewed as part of a National Strong-Motion Program and the individual efforts more effectively coordinated.

The panel agrees with this statement and, for purposes of the present panel report, the totality of strong-motion activities in the United States is called the U.S. Strong-Motion Program. This name is in recognition of the fact that there is a commonality of interest and purpose among those involved in strong-motion activities which bears on public safety and welfare. The name does not imply any formal administrative structure but, rather, implies that an objective overview of the various activities can be of mutual benefit to the individual strong-motion programs and to the country as a whole. The name is used in this report in the same sense that it was used in the workshop report.

EARTHQUAKE ENGINEERING BENEFITS OF THE U.S. STRONG-MOTION PROGRAM

Before the recording of strong earthquake ground motions there was no reliable knowledge of the nature and intensity of earthquake shaking. The earthquake-resistant design of buildings was based on a simplified concept of "equivalent static force," which did not provide a uniform factor of safety for different structures and in many cases did not provide adequate protection.

When the first strong-motion records were obtained, it was necessary to rethink earthquake engineering design. As data accumulated and were analyzed, building codes were modified, seismic zoning maps were redrawn, and innovative dynamic analyses and designs were made for important structures. This led to the improved performance of buildings during earthquakes and to greater public safety. The benefits of the strong-motion program have been especially important for projects requiring an exceptionally high degree of safety, such as nuclear power plants, offshore oil drilling platforms, and major dams.

Since the location and timing of earthquakes cannot be specified in advance, it is not always possible to have strong-motion instruments in position to record destructive motions of ground and structures. Therefore, the accumulation of data has not been as rapid as desired. In recent years, some valuable records of very strong ground shaking and the resultant vibrations of buildings have been obtained. These data have led to improvements in building design and in earthquake resistance of manufacturing facilities and urban lifelines.

In the United States, only limited data have been obtained during large earthquakes of magnitude greater than 7, and no strong-motion records have been obtained during great earthquakes of magnitude 8 or larger. (For large earthquakes it is customary to measure the magnitude in terms of the strength of the low-frequency wave radiation. The numerical value of such a magnitude will be greater for large earthquakes than a magnitude based on the strength of the high-frequency wave radiation. The latter magnitude often is used to designate the size of minor to moderately large earthquakes.)

Also, there has been only one instance where the motions of a building were recorded while it was shaken to the point of severe structural damage. Although numerous buildings collapsed during the September 19, 1985 Mexico earthquake, no records were obtained of building motions.

Thus, there is a need for additional strong-motion records, which presumably will be provided by future earthquakes, and there is a need for the information they contain to be readily available to potential users. It is well established that the improvements in earthquake resistance made possible by the accumulation of strong-motion records to date have reduced casualties and damage losses.

PRESENT STATUS OF U.S. STRONG-MOTION ACTIVITIES

INTRODUCTION

Strong-motion programs in the United States have been instituted and presently are operated by federal, state, and local government agencies, universities, and industrial and nonpublic organizations. A number of federal agencies, such as the U.S. Army Corps of Engineers,* the Bureau of Reclamation, and the Veterans Administration, retain the U.S. Geological Survey (USGS) to install and maintain their strong-motion instruments and to process the data. Other federal agencies, such as the Naval Facilities Engineering Command, install and maintain their instruments but have the USGS process the data. All of these instruments, together with those operated by the USGS under its own program, make up what USGS calls the U.S. National Strong-Motion Network. Still other federal agencies, such as the Nuclear Regulatory Commission and the national laboratories of the Department of Energy, install and maintain their instruments and process the data produced by them or contract this work to other organizations.

Primary centers for the distribution of strong-motion data in the United States are the USGS in Menlo Park, California; the National Geophysical Data Center (NGDC) of the National Oceanic and Atmospheric Administration (NOAA) in Boulder, Colorado; the California Division of Mines and Geology in Sacramento; the University of Southern California in Los Angeles; and the California Institute of Technology in Pasadena. (It is understood

*In the western United States the Corps' instruments are maintained by the U.S. Geological Survey and in the east by the Corps' Waterways Experiment Station.

that because of budgetary constraints, consideration is being given to closing down the NGDC strong-motion data activities, and USGS is considering the dissemination of its own strong-motion data if NGDC ceases this activity.)

The California Division of Mines and Geology operates a large strong-motion program that involves the installation and maintenance of accelerographs and the processing of data. The state of Washington also has a strong-motion program with a significant number of instruments. Some electric power companies maintain networks of strong-motion instruments, such as Pacific Gas and Electric Company and Southern California Edison Company. Several universities have strong-motion networks that are maintained for research purposes. A number of local government agencies maintain instrument networks and a large number of buildings have been instrumented by the owners according to the requirements of the Uniform Building Code and the Los Angeles City Building Code. Some industrial corporations have also installed instruments.

The methods of processing and analyzing strong-motion data were originally developed at the California Institute of Technology, and processed accelerograms were published in a series of "Strong-Motion Data Reports." These methods are now employed by such organizations as the USGS and the California Division of Mines and Geology. As new developments in instruments are made and as improved methods of analysis are developed, it can be expected that strong-motion data processing will become more efficient.

U.S. DATA ACQUISITION

As of 1985 nearly 3,000 modern film-recording and digital strong-motion accelerographs are estimated to have been deployed in the United States. These instruments have been installed in a variety of geographical locations; some in the free-field, some in buildings, and others on dams, power plants, bridges, storage tanks, manufacturing facilities, and other structures. A sizable number, perhaps 40 percent of the total, are intended for special-purpose use and their data generally are not available to the research community. Figures 4 and 5 show the locations of accelerographs inside and outside of California as of 1981. These figures do not include instruments required by building codes, those in commercial nuclear-powered electrical generating plants,

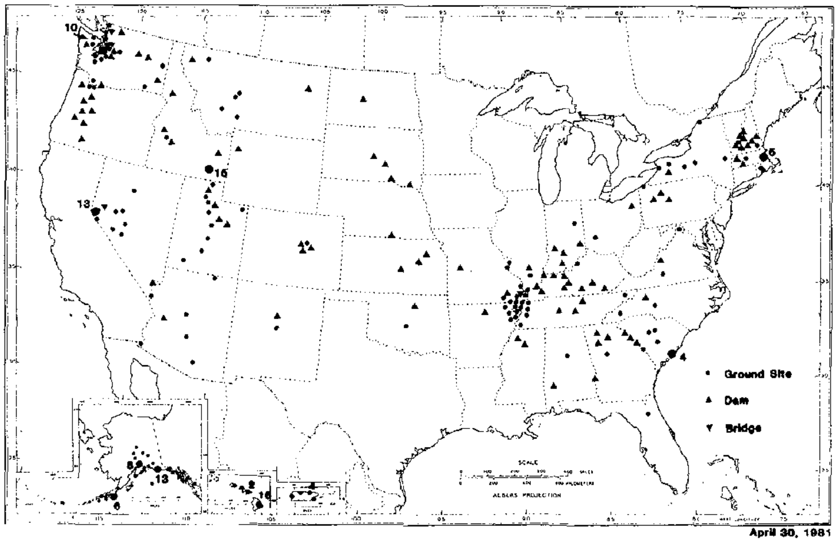

FIGURE 4 Known accelerographs in the United States outside of California as of April 30, 1981. Excludes commercial nuclear-powered electrical generating plants. (From Seismic Engineering, U.S. Geological Survey)

and some others. Figure 6 shows the locations of epicenters of damaging earthquakes in the United States through 1971.

Strong-motion instruments are owned and operated by a large number of different organizations and government agencies. A partial list of sponsors of major strong-motion activities is given with descriptive data in the Appendix. (This list is an update of information compiled for the U.S. National Workshop on Strong-Motion Earthquake Instrumentation.)

At the federal level, owners of the largest numbers of strong-motion instruments* are the U.S. Army Corps of Engineers (350 instruments) and the USGS (275 instru-

*To date, 187 dams have been identified as having strong-motion instruments installed and in operation. About 680 strong-motion instruments are installed at these locations. Of these 187 dams, 112 are instrumented by the Corps and 24 are instrumented by the U.S. Bureau of Reclamation. About 40 percent of the dams are in California and 30 percent are east of the Mississippi River. Of the 56 identified as large U.S. dams, only 19 are instrumented (United States Committee on Large Dams, 1985).

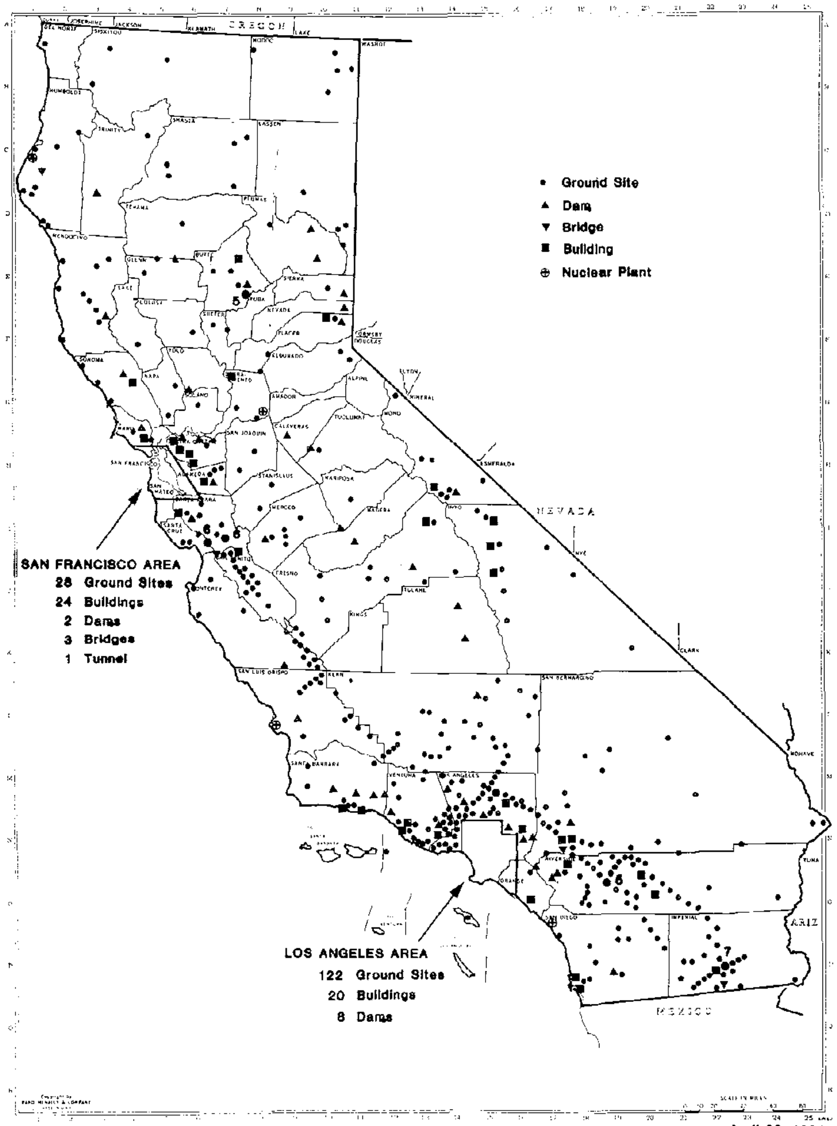

FIGURE 5 Known accelerographs in California as of April 30, 1981. Excludes instruments required by building codes. (From Seismic Engineering, U.S. Geological Survey)

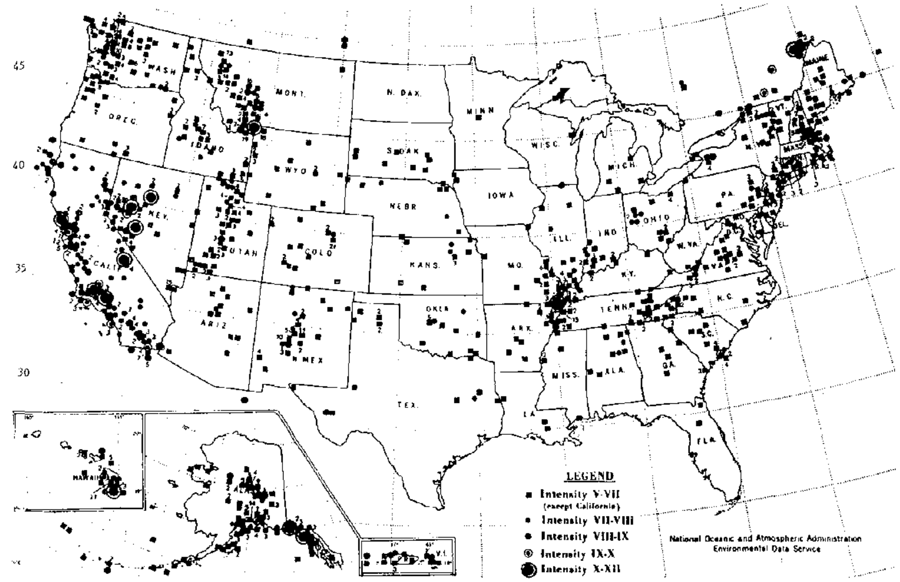

FIGURE 6 U.S. earthquakes of Modified-Mercalli Intensity (MMI) V - XII. Intensity VII shaking is strong enough to damage some weak structures; intensity VIII or greater corresponds to severe damage. The MMI number is based on subjective estimation of degree of damage and, hence, is not a reliable measure of the ground shaking. The installation of strong-motion accelerographs is of such recent date that only a small percentage (1 to 2 percent) of the events plotted in this diagram had ground motion recorded by these instruments. A larger percentage were recorded by sensitive seismographs that can record earthquakes at long distances. Source: National Oceanic and Atmospheric Administration (1973).

ments) followed by the Department of Energy (80 instruments), the Bureau of Reclamation (70 instruments), and the Veterans Administration (65 instruments). The location and placement of instruments is generally determined by the owning agency's goals and priorities.

The USGS operates a national strong-motion network consisting of about 1,100 instruments owned by various federal agencies and organizations and deployed nationwide. This network is a major element of present national strong-motion activity. The USGS has prepared a draft plan for an enlarged strong-motion instrument program (Spudich et al., 1985).

The U.S. Navy has a strong-motion program that is not part of the USGS network in the sense that it installs and maintains its own instruments, although it makes use of the USGS data processing capabilities. In 1979, the Naval Facilities Engineering Command (NAVFAC) authorized the Naval Civil Engineering Laboratory (NCEL) to acquire and install accelerographs at naval installations subject to high seismic risk. These included massive and unique structures, such as graving drydocks, cantilever plane hangers, and power plants, that were near the waterfront and located in remote regions (e.g., Guam) having no available strong-motion data. Presently, 7 accelerographs are located in Washington; 14 in California; 2 at Charleston, South Carolina; 2 in Alaska; 3 in Guam; 2 in Puerto Rico; 2 in the Philippines; and 3 in Italy.

The largest nonfederal program is that of the state of California, and it is also the largest individual program in the United States. The California Strong-Motion Program has about 500 instruments installed in the free field and in structures. It is supported by a fee on new construction within the state and is managed by the California Division of Mines and Geology, with general policy oversight provided by the California State Seismic Safety Commission. The California Strong-Motion Program is one of the few inclusive programs covering installation, maintenance, data processing, and dissemination. This program, together with the USGS program, would be a key element in a future national strong-motion program.

At the time of the San Fernando earthquake of 1971, the city of Los Angeles maintained one of the largest networks of strong-motion instruments. These instruments, installed primarily in new medium- to high-rise structures, were mandated by law. Since 1982, the Los Angeles program has been incorporated into the California Strong-Motion Program.

Originally the network was maintained by the Seismological Field Survey (SFS) without being funded. The records obtained during the 1971 earthquake were processed and disseminated by the SFS. When the SFS was merged into the USGS the decision was made not to maintain the Los Angeles city network, and for a few years the Department of Building and Safety of the City of Los Angeles maintained the network. In 1982 Los Angeles joined the California State Strong-Motion Program and each existing building owner was directed to arrange for the maintenance of his instruments and an annual deposition was required to certify that the instruments were in working order. Some 44 smaller cities using the Uniform Building Code also require taller buildings to be instrumented, but Los Angeles is the only city with a large number of instruments in place. The instruments mandated by cities through the building code represent a large, uncoordinated, and unplanned network.

In addition to these strong-motion activities, there are a number of other important efforts undertaken by universities, public utilities, state and local government agencies, and some private corporations. Generally speaking, these instrumentation activities are directed toward specific research or decision-making objectives. A future national program must integrate these activities as well.

It should be noted that although many of the strong-motion instruments have been installed by organizations with special purposes in mind the recordings may be of great value to researchers and designers. For example, the famous Pacoima Dam accelerogram was recorded by one of the instruments installed by the Los Angeles Flood Control District; the much studied Santa Felicia Dam records were recorded by instruments that had been installed by the United Water Conservation District of Ventura County. The records of the 1966 Parkfield earthquake, which provided a significant advance in seismological knowledge, came from an instrument array that had been installed across the San Andreas fault by the California Department of Water Resources to provide information for the design of the California Water Project, which brings water from the Feather River in northern California to southern California. These examples show the importance of coordinating all strong-motion activities through a national program.

Funding for federal strong-motion activities is provided through the budgets of the federal agencies involved. Some of this funding, primarily that for activities of the NSF and USGS, falls under the Earthquake Hazards Reduction Act. However, the activities of many agencies such as the U.S. Army Corps of Engineers, Department of Energy, Bureau of Reclamation, and Veterans Administration do not come under the act. U.S. Geological Survey expenditures for strong-motion activity are primarily inhouse; the USGS supports very little university or private strong-motion research.

The major source of funding for university research and other nongovernmental activity in strong-motion measurement is provided by the NSF under the Earthquake Hazards Reduction Act. Within the NSF, only the Engineering Directorate funds strong-motion instrumentation research. The Earth Sciences Division does not support such research, and this has created tension between the engineering and seismological components of strong-motion research. More importantly, as a consequence, some significant research programs proposed by the university community have not been supported.

U.S. DATA MANAGEMENT

Many organizations (i.e., government agencies, private and public utilities, universities, and a few private organizations) are involved in U.S. strong-motion programs in varying degrees. The NGDC, USGS, and California Division of Mines and Geology have undertaken the task of managing strong-motion data (i.e., archiving, cataloging, and disseminating the data). The USGS maintains the Strong-Motion Information Retrieval System (SMIRS), which can be easily accessed by outside users (Converse, 1978). Data on causative earthquakes, strong-motion stations, and available recorded accelerograms can be retrieved using any computer terminal and a 300-baud modem.

While SMIRS does provide limited information to aid the user, it does not provide the strong-motion records themselves or information relative to these records, although the system does indicate where these records may be obtained. SMIRS is generally limited to data from the Western hemisphere, although it contains some information on large-magnitude earthquakes elsewhere.

The USGS archives the originals of its strong-motion records and those from other agencies it serves. Significant records are digitized and processed. These data are kept within the USGS and duplicate data are sent to the NGDC in Boulder for distribution to users; this procedure considerably delays data availability. The California Strong-Motion Program also sends copies of its processed data to NGDC.

The California Division of Mines and Geology collects, processes, and archives its own data and distributes them upon request. It also has a data retrieval system similar to SMIRS. The Division's data processing, archiving, and retrieval systems were modeled on the USGS program.

The University of Southern California maintains an array of 80 strong-motion instruments in metropolitan Los Angeles for research purposes (Lee and Trifunac, 1982). It also has a data retrieval system that can provide digitized data via telephone.

Some smaller programs, such as those at the California Institute of Technology, Southern California Edison, and Pacific Gas and Electric, also have data processing, archiving, and dissemination capabilities. However, these services are not well publicized, the organizations involved have generally not made arrangements for sending the data to NGDC, and in certain instances the procedure to acquire data is not well known.

The Environmental Data Information Services (EDIS) of NOAA operates both the NGDC and the World Data Center.* Hypocentral data, intensity data, and tsunami data files are maintained for worldwide earthquakes. Worldwide standard network seismograms and strong-motion accelerograms are archived and catalogued (Morris et al., 1977). The strong-motion records are generally confined to U.S. earthquakes, and about 3,000 records are on file.

The NGDC has about 1,000 processed accelerograms from other countries. The degree of processing varies from digitized-uncorrected to completely corrected accelerograms using methodologies originally developed at the California Institute of Technology (Trifunac and Lee, 1973). However, some of the processed strong-motion accelerogram files are not complete, especially those of other countries. Nearly all of the important U.S. records are with the NDGC, but many processed records are still in the possession of individual organizations.

EDIS will supply any of its processed accelerograms to users upon written request. A fee is required to cover handling costs. NGDC has its strong-motion data cataloged to the extent that users can identify the records they would like to receive. However, the catalog is not sufficiently complete for research purposes. The strong-motion data services provided by NGDC are valuable to earthquake engineers and to seismologists studying

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*Budgetary contraints have caused NOAA to decide to phase out the World Data Center activities and to consider phasing out the NGDC strong-motion activities.

macroseisms and should be continued. It is recommended that the proposed joint subcommittee, and users of the data, consider ways of expanding the strong-motion services of NGDC, supplementing and/or complementing them with other data centers and resources.

DATA APPLICATIONS

Applications of strong ground-motion data take a variety of forms. For the purposes of this report they are arbitrarily divided into (1) basic seismological and engineering seismology research, (2) basic earthquake engineering research, and (3) engineering practice and code development.

Basic Seismological and Engineering Seismology Research

Strong-motion data contribute to the understanding of source mechanisms and propagation of seismic waves from the source to the point of interest, including local site effects (see Figures 7 and 8). The characteristics of the source mechanism that can be examined using strong-motion data include: rupture velocity, point of initiation of the rupture, asperities or irregularities on the fault that produce strong radiation of high-frequency seismic waves, the direction of fault-rupture and the resultant pattern of wave radiation, spectral content, stress drop, fault-rupture dimensions, time sequence or slip rate of fault motion, strength of energy release or seismic moment, type of ground rupture, and possible regional differences in these parameters. An enhanced knowledge of the physics of the source is valuable not only to the science of seismology but also for the estimation of strong ground motion for engineering applications.

Strong ground-motion data also contribute to a better understanding of wave propagation characteristics, such as geological and physical characteristics of the wave path (e.g., velocities, density, and rigidity); attenuation along the path, both geometric and that from anelasticity; scattering effects; near-source parameters (e.g., coupling, reverberation, and focusing) due to topography or other structural elements; and site effects caused by variations in soil type, water table, and neighboring geologic structure and topography. The resultant strong-motion duration and frequency content

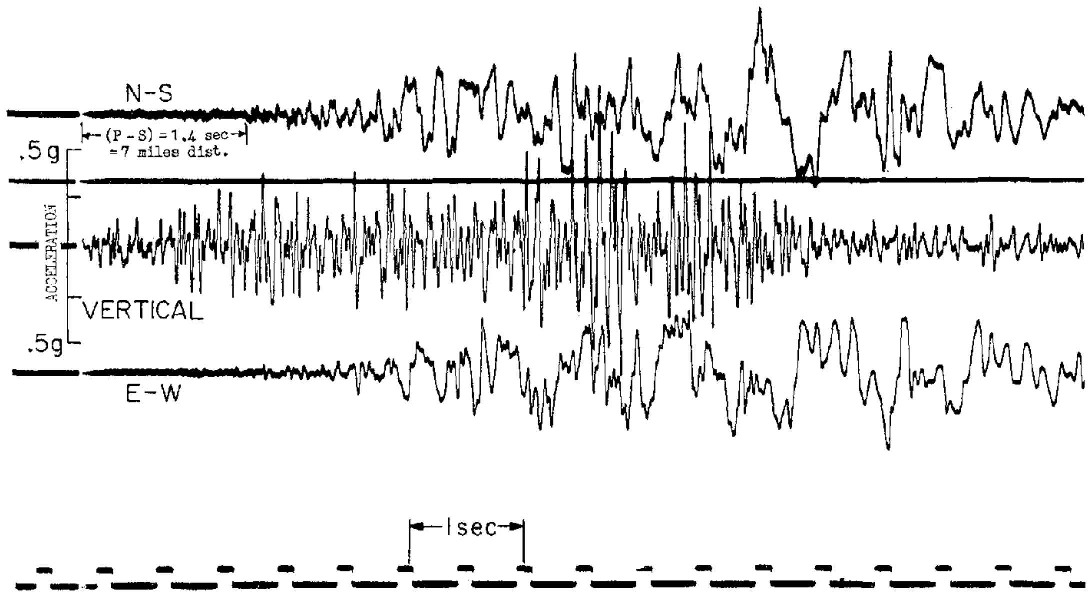

FIGURE 7 Accelerogram recorded during the Westmorland, California earthquake of April 26, 1981. This earthquake occurred on the Imperial Fault, which extends from Mexico into the United States and is located 100 miles east of San Diego. The accelerograph was close to the point of initial fault rupture as evidenced by the short delay between the arrivals of the primary and secondary (P-S) seismic waves. The P-S delay of 1.4 seconds corresponds to a slant distance of 7 miles. The strong phase of shaking lasted about 4.5 seconds and was of damaging strength. (From the Strong Motion Instrumentation Program of the California Division of Mines and Geology)

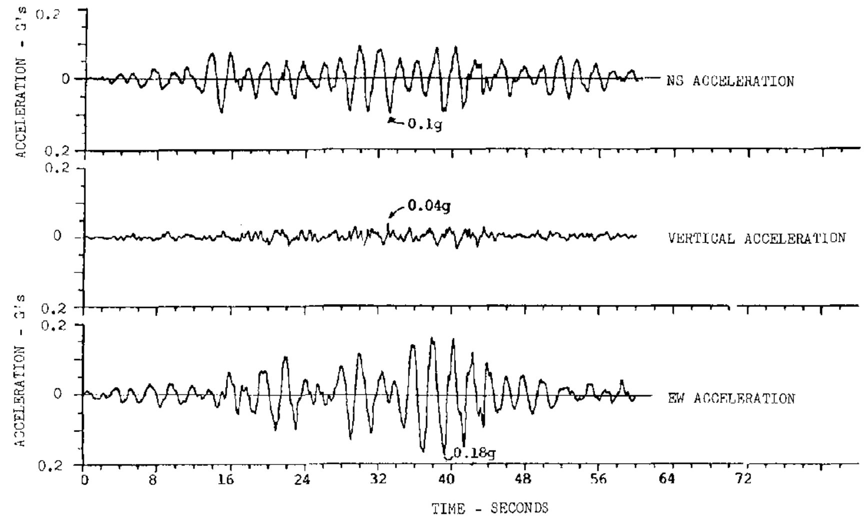

FIGURE 8 This accelerogram, which differs greatly from that shown in Figure 7, was recorded in the center of Mexico City during the September 19, 1985 earthquake. This magnitude 8.1 shock was generated by slip on a subduction fault about 200 miles southwest of Mexico City, where some 400 multistory buildings were severely damaged or collapsed. The center of the city was built on a layer of soft clay which, as the accelerogram shows, vibrated strongly with a dominant period of 2 seconds. This explains why buildings with a fundamental period in the range of 1 to 3 seconds were much more strongly affected than buildings whose periods were outside of this range. It also explains why damage was minimal in those parts of the city built on firm ground. (Accelerogram courtesy of the Instituto de Ingenieria, Universidad Nacional Autonoma de Mexico).

are strongly affected by the characteristics of the propagation path as well as the duration of the earthquake source. Strong regional differences have been observed in high-frequency wave propagation in various parts of the United States.

Adequate strong-motion instrumentation, including two- and three-dimensional arrays, is required to obtain the basic data for better understanding the seismological source and propagation parameters. This enhanced understanding will significantly improve the U.S. capability to predict ground motion in a given geologic environment.

Basic Earthquake Engineering Research

Over the past 40 years, the specialized field of earthquake engineering has grown from infancy to its current advanced state, allowing the design and construction of buildings with greatly improved safety and cost-effectiveness. This progress could not have taken place without the availability of strong-motion accelerograms and high-speed digital computers that together enabled the development and implementation of the current methodologies of analysis and design.

The research that played a major role in the development of these methodologies can be classified into four areas: (1) seismic ground motions, (2) mathematical modeling and dynamic analysis, (3) structural performance, and (4) seismic design.

Strong Ground Motions

Understanding the nature of strong ground motions, i.e., intensity, frequency content, phase relations, duration, and spatial variations, is fundamental to achieving good earthquake-resistant design of critical structures based on economic and safety considerations. These structures include buildings, bridges, dams, offshore platforms, liquefied natural gas storage tanks, and nuclear power plants.

Through the improved strong-motion instrumentation program, much valuable information has been recorded that has led to a greater understanding of the expected ground motions required in the design process (see Figure 8). The ground-motion criteria used for earthquake-resistant design of critical structures have undergone major revisions in recent years because of recorded ground

ground motions. Further revisions can be expected as new knowledge is gained through the strong-motion instrumentation program.

Mathematical Modeling and Dynamic Analysis

Because of the availability of high-speed digital computers, it is possible to perform the numerical work required by detailed mathematical models of critical structures. Twenty-five years ago the practicing engineering profession was very limited in its ability to calculate seismic response. Presently, however, detailed dynamic analyses are routinely carried out for important structures.

For example, seismic response analyses of nuclear power plants containing a multitude of piping systems, equipment, and secondary structures are made, including soil-structure interaction effects. These design activities set up a demand for research and development toward improved mathematical modeling which, in turn, creates a demand for improved knowledge of strong motion.

Structural Performance

Because of economic considerations, controlled damage must be allowed to take place in many structures, such as buildings, offshore platforms, and bridges, during maximum credible earthquake conditions. This requirement necessitates an understanding and an ability to predict the resisting forces developed under large deformation cyclic conditions and the failure mechanisms likely to take place under extreme conditions. With the availability of modern electronically controlled, hydraulically powered testing equipment and shaking tables, high-speed data acquisition and processing equipment, and computers and associated computer programs for control and analysis, much knowledge has been recently gained regarding structural performance under seismic conditions. The validity of this knowledge is, of course, highly dependent upon the ability to prescribe realistic seismic excitations, which is dependent upon information gained through the strong-motion instrumentation program.

Seismic Design

The practice of earthquake engineering in the design and construction of structural facilities has undergone major changes during the past 25 years as a result of advances made in the areas of seismic ground motions, mathematical modeling, dynamic analysis, and structural performance. Codes have been modernized, requiring the designs to be based on more realistic seismic ground-motion criteria, better detailing of structural components and systems, and improved control of materials.

Considering that basic earthquake engineering research leads to economic and safety improvements in seismic design and construction, it is very clear that every effort should be made to strengthen the strong-motion instrumentation program, which is fundamental to this development. The cost/benefit ratio is brought into better focus when considering that about 35 percent of the roughly $230 billion spent annually on construction in the United States is for regions of moderate to high seismic activity. Many of these regions are outside of California. Figure 2 is a photograph of a collapsed building in Charleston, South Carolina in 1886. Figures 9 through 14 are examples of earthquake damage caused by the 1964 Alaska, 1962 Mexico, 1982 Coalinga (California), and 1979 Imperial County (California) earthquakes.

Engineering Practice and Code Development

Accelerogram data have also led to improvements in U.S. building codes. For example, the evolution of the lateral force provisions in these codes is based on the accelerograms recorded during major earthquakes (Figures 7 and 15). More accelerogram data are required, however, because of the need for further improvements in engineering practice and building codes. Accelerograms have not been recorded near the fault ruptures of U.S. earthquakes greater than magnitude 7, although these pose the largest threat to many urban environments. Engineers rely on extrapolations of the existing data base to predict the motions of these potentially destructive events. As a result, the uncertainty in these estimates is greater than those where little or no extrapolations are involved. Consequently, the design of future structures may not be optimal and the evaluation of existing ones may be inaccurate in some cases.

FIGURE 9 This six-story, reinforced-concrete apartment building vibrated strongly before collapsing during the 1964 Alaska earthquake. It was newly built in Anchorage and was a lift-slab type, relying on the two vertical elevator/stair shafts to provide earthquake resistance. There were no recording instruments in or near the building. (Photo by George W. Housner)

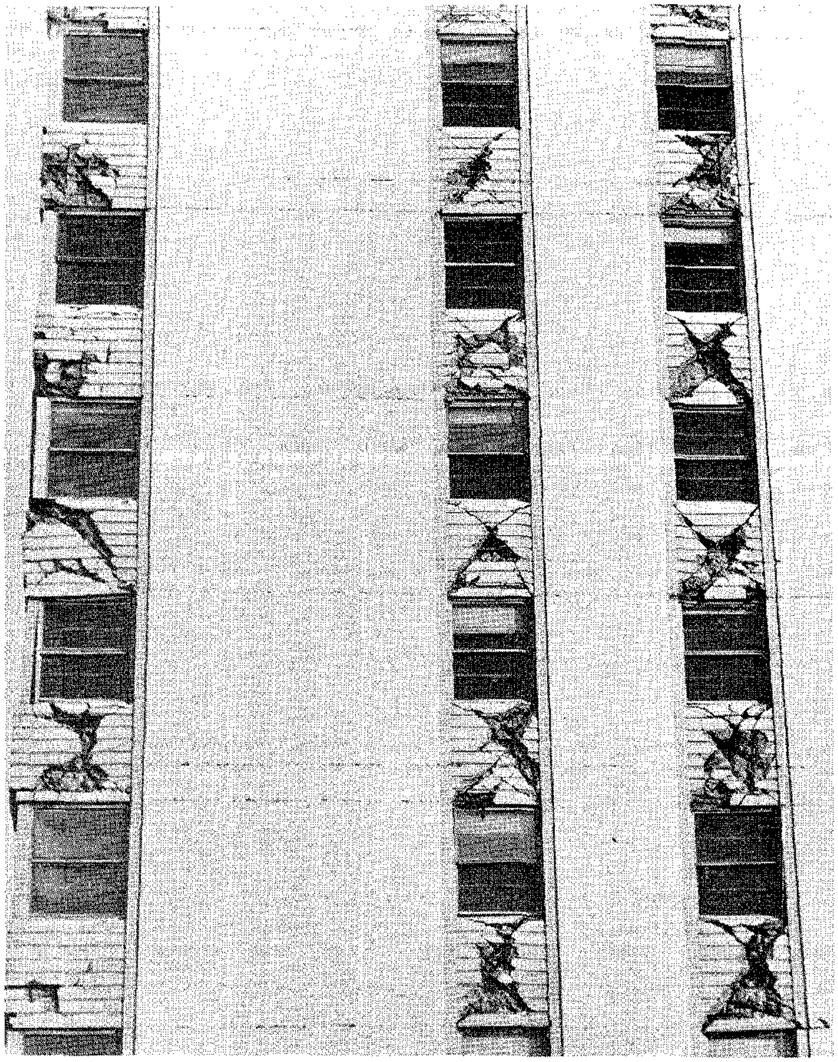

FIGURE 10 This 14-story, reinforced-concrete apartment building in Anchorage, Alaska was damaged by the vibrations produced by the 1964 Alaska earthquake (M8.4). There were no recording instruments in the building, nor were there strong-motion instruments in Alaska at that time. (Photo by George W. Housner)

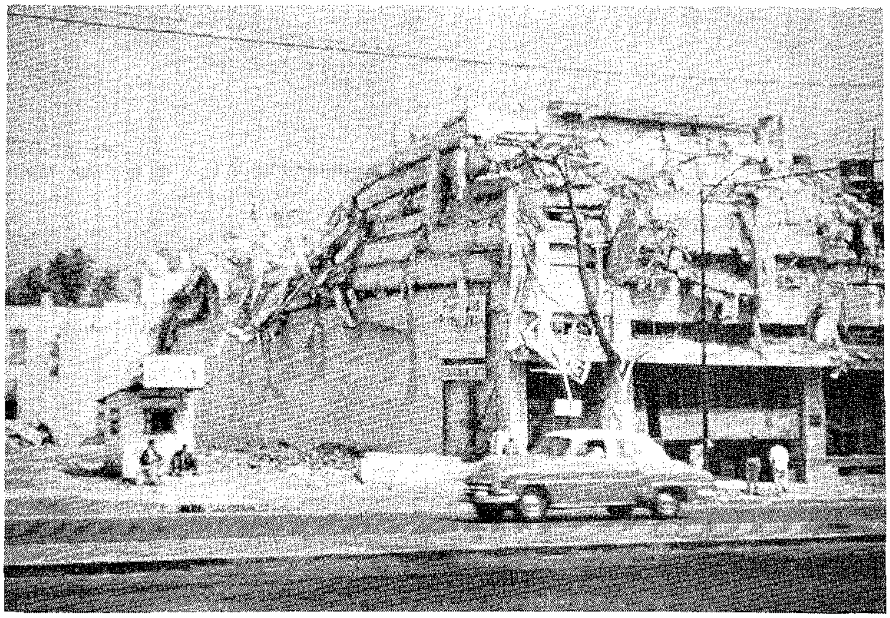

FIGURE 11 Collapse of an eight-story building in Mexico City in 1957. Such collapses, in which the floors are stacked like a deck of cards, have been observed in several earthquakes. The epicenter of the 1957 Mexico earthquake was 200 miles south of Mexico City. Similar collapses occurred during the September 19, 1985 Mexico earthquake. Buildings that were not designed to resist earthquakes are especially susceptible to damage from distant events. (Photo provided by George W. Housner)

FIGURE 12 Structural damage in the Coalinga business district resulting from the May 2, 1983 earthquake (M6.5). Source: California Division of Mines and Geology (1983). (Photograph by James Stratta)

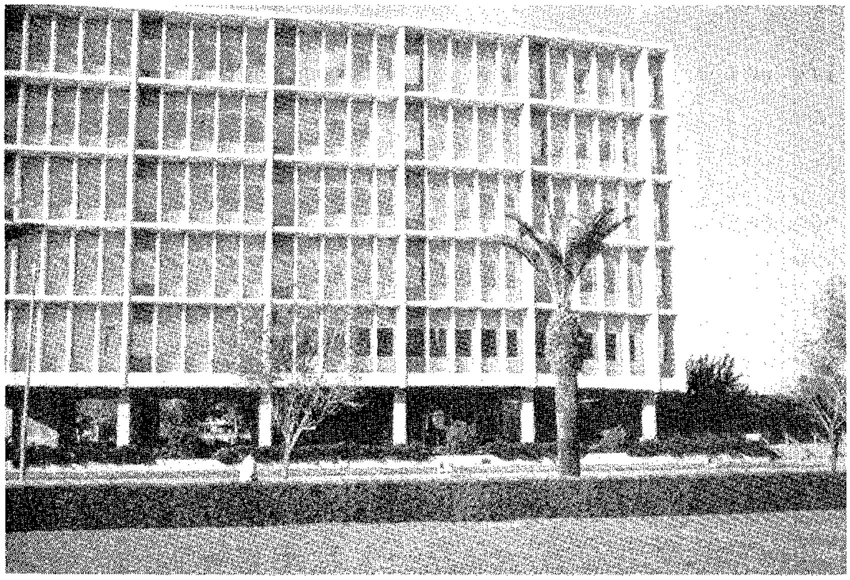

FIGURE 14 View of the south side of the Imperial County Services Building. This structure was severely damaged by the Imperial County earthquake of October 15, 1979 (M6.5). The first-story reinforced-concrete columns were badly cracked at top and bottom. The four columns at the east end of the building were shattered at the bottom and dropped the east end of the building about 10 inches. The building was demolished later. Strong-motion instruments had been installed in the building prior to the earthquake, and these recorded the motions of the roof, several floors, and the ground. Source: California Division of Mines and Geology (1983). (Photo by C. R. Real)

FIGURE 13 Structural damage to a brick building resulting from the Coalinga earthquake of May 2, 1983. The epicenter of this magnitude 6.5 shock was about 10 miles from the town. Such buildings, not designed to resist earthquakes, are very vulnerable to damage. Source: California Division of Mines and Geology (1983). (Photograph by James Stratta)

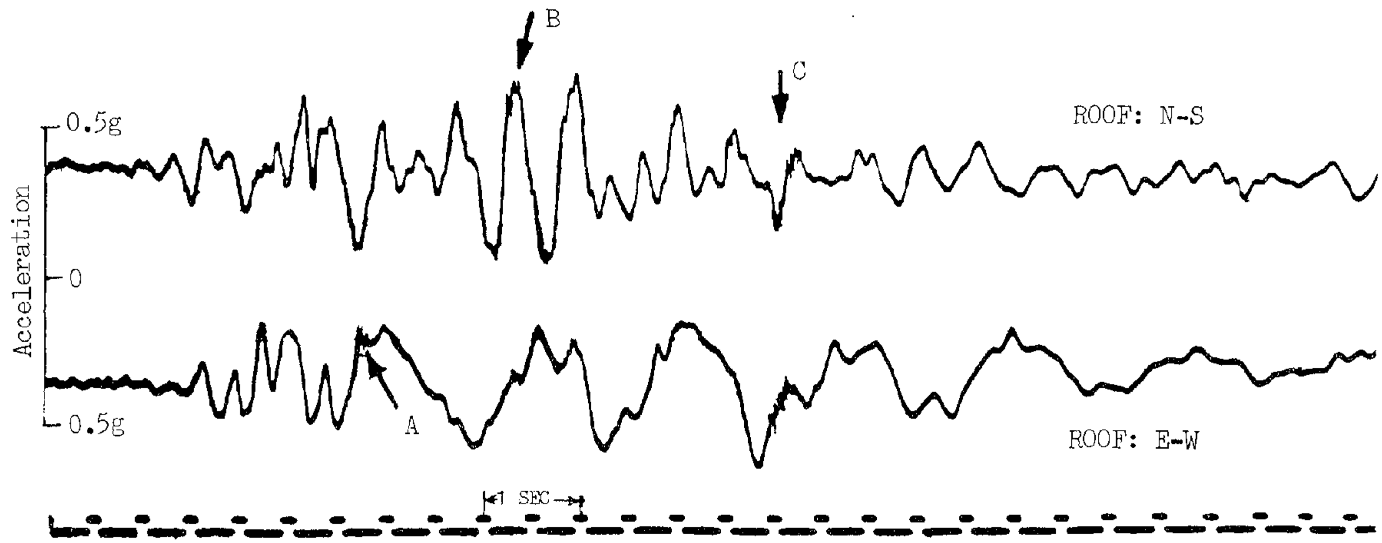

FIGURE 15 Recorded acceleration of the roof of the Imperial County Services Building. The building was about five miles from the causative fault. This six-story reinforced-concrete building had earthquake resistance provided by a beam and column framework in the east-west direction, and by stiff shear walls in the north-south direction. At time A the columns in the first story cracked at the top and bottom, and this partial hinge action greatly reduced the stiffness and increased the natural period of vibration. At time B cracks developed in the shear walls. At time C the four columns at the end of the building shattered at the bottom and dropped the end of the building 10 inches. This is the only time that records were obtained in a building undergoing severe damage. (From the Strong Motion Instrumentation Program of the California Division of Mines and Geology)

INTERNATIONAL ACTIVITIES

There are many regions of the world that face an earthquake threat even greater than that of the United States. Recognizing this threat, some foreign countries have developed significant strong-motion programs. Most notable is a program in Japan that could serve as a model for other countries. There are over 1,500 strong-motion instruments installed in the free-field and in structures in Japan. In addition, Japan has embarked upon a nearly $15 million program for the installation of dense strong-motion arrays. The area of Japan is 1/25th that of the United States while its population is half as large. The resulting concentration of people and industries gives great importance to earthquake hazard.

Other countries with active strong-motion programs include Algeria, Chile, China, India, Iran, Italy, Mexico, New Zealand, Russia, Taiwan, Turkey, Venezuela, and Yugoslavia. While earthquake mechanisms and construction techniques may vary in different parts of the world, the free-field and structural data obtained from a major earthquake anywhere in the world are valuable to all earthquake researchers.

In 1978, an International Workshop on Strong-Motion Earthquake Instrument Arrays, with principal support from the National Science Foundation, was held in Hawaii (Iwan, 1978). The workshop's goal was to develop a workable plan for the future deployment of dense strong-motion arrays with primary emphasis on ground-motion studies. Based on careful examination of the seismicity and geology of various worldwide sites, the workshop selected 28 sites for possible deployment of strong-motion arrays. The workshop also unanimously adopted a resolution calling for the design and installation of strong-motion arrays worldwide and the creation of an International Strong-Motion Array Council (ISMAC). Since the workshop, a number of new strong-motion array and network programs have been instituted and large earthquakes have occurred at a significant number of the sites.

The ISMAC was established in 1979 under the auspices of the International Association for Earthquake Engineering and the International Association of Seismology and Physics of the Earth's Interior. The council is involved in coordinating the activities of national and regional strong-motion programs and in the promotion of worldwide assembly and dissemination of strong-motion data. Engineers and scientists from the United States play an active role in the council.

The higher seismicity of some regions outside of the United States affords the opportunity of obtaining essential strong-motion data more quickly than relying solely upon domestic measurements. Also, special instrumentation installations set up to measure aftershocks following a major seismic event somewhere in the world can provide a rich source of strong-motion data. For these reasons, it is important that the U.S. strong-motion program have an international perspective.

Cooperative programs in strong-motion studies have recently been established between the United States and India, Taiwan, China, and other countries. Some of these cooperative projects have already yielded significant data.

3

NEED FOR FURTHER DEVELOPMENT OF U.S. STRONG-MOTION ACTIVITY

Although much progress has been made in U.S. strong-motion activity since its inception in 1932, there is a need for further development in the areas of instrumentation, data acquisition and management, data analysis and research, and applications.

INSTRUMENTATION

Recent advances in technology offer new opportunities for improving the quality and computer accessibility of strong-motion data. Improved hardware components permit greater frequency bandwidth, wider dynamic range, and less power consumption. Microcomputers allow software control of various hardware components, efficient and reliable execution of system tasks, increased flexibility in system design, and increased digital processing capabilities. Modern storage media extend data capacity and provide compatible formats for minicomputer systems, which when deployed in the field permit extensive preprocessing of large volumes of data during field experiments.

Research instruments, such as the GEOS, have incorporated many of these features of modern technology and established the feasibility of incorporating such characteristics in instrumentation needed for future arrays in the United States. Several of these features have been recently incorporated in commercial instrumentation, such as the PDR-2, PDR-1, DR-200, A-700, and DSA-3. However, no commercially available instrumentation has yet taken full advantage of available technology. Increased use of available technology is strongly needed in the United States. For example, in Japan 16-bit (96 dB), computer-compatible, cartridge recorders are used as standard recorders in arrays such as those installed by the Public Works Research Institute.

The very destructive ground motions in Mexico City during the earthquake of September 19, 1985 were recorded by several digital accelerographs that were installed and maintained by the Institute of Engineering of the National University of Mexico. The tape cassettes were retrieved the same day, the data were processed through standard California Institute of Technology computer programs and graphs of acceleration, velocity, and displacement as well as response spectra were available the following day. Photocopies were being studied in the United States two days later. This ready availability of the strong-motion data was very important in the explanation and understanding of the collapses of multistory buildings. In view of this, the panel recommends that those locations in the United States where significant earthquakes are expected, for example the Los Angeles region, be instrumented with some digital accelerographs to supplement the analog instruments already installed. This will enable some data to be disseminated within a day, or two, of the earthquake.

To date, little modern digital strong-motion instrumentation has been installed in the United States. Resources are needed to develop a reliable low-cost digital accelerograph for commercial production and routine incorporation into planned arrays. The accelerograph should incorporate modern technology, minimize network maintenance costs, and be developed to incorporate appropriate components of recently developed research instrumentation. Miniaturization of the modular components of research instrumentation would permit the development of a compact, low-power, wide dynamic range, broad bandwidth digital recorder capable of recording data of substantially improved quality at lower cost and in a more accessible form for use by the scientific and engineering communities.

Development of an inexpensive modern digital recorder could greatly accelerate the deployment rate of recorders on a worldwide basis and could serve as an instrumentation standard for a worldwide network of strong-motion instrumentation, which is one of the fundamental objectives of the International Decade for Hazard Reduction. Such a network would significantly increase the probability of documenting accurately the near-source seismic radiation field of a tremendous earthquake and its effect upon man-made structures. Such a data set remains to be collected for a large magnitude earthquake anywhere in the world.

DATA ACQUISITION AND MANAGEMENT

The acquisition of larger amounts of strong-motion data by a variety of organizations results in an increasing need to develop data archiving, management, and retrieval procedures that will increase data accessibility for research and engineering applications. The increasing amounts of data and rapidly changing computer technology suggest that a data-base management system using computer-industry-support software would be most appropriate. Preferably such a system would be based on commercially available software products to facilitate compatibility with future hardware changes. The ideal system or parts of the system should be reasonably transportable between mid-sized computers, so that the system may be maintained by appropriate agencies and research institutions. A user-friendly data-management system permitting ready access to complete strong-motion time series and spectral data bases is a fundamental need of both the scientific and engineering communities. A prime consideration is that strong-motion accelerograms be made available without delay after an earthquake to designers, researchers, and others who have a need to see the recordings.

The volume of digital data suggests the need for a data archiving and retrieval system involving two components. One component should provide a catalog of information regarding station, event, and data parameters. A second component, involving a much larger volume of information, should provide the actual time series and spectral values. The first component should be interfaced with the second component to facilitate archiving and retrieval of the time series. The first component of the system should be maintained by appropriate data-collection agencies with maintenance of the second component depending on resources and objectives of the agency. These two interactive components suggested for a data-base management system are consistent with present uses of strong-motion data. Scientific and engineering applications of strong-motion data are generally of two types: parametric studies and studies involving the complete time series or derived spectra.

The Strong-Motion Information Retrieval System of the U.S. Geological Survey is the first example of a parameter-based information system applied to strong-motion data. A similar system, though possibly simplified, seems the most appropriate for meeting the needs of parametric investigations. Specifically, the system should be an online system allowing access to certain sets or subsets of data characterized and selected on the basis of key parameters. A three-segment data base, composed of data related to accelerograms, recording stations, and triggering earthquakes similar to the division used by Crouse et al. (1980), may be the most practical. A parameter-based online retrieval system is a particularly appropriate scheme for providing timely access to newly recovered data. Such a parameter data-base system could be used to define access to the much larger data base consisting of original and processed time series and spectral data.

Maintenance of a complete strong-motion time series and spectral data base for access in an online environment may not be practical at present, considering the volume of data, disk-storage costs, and data transmission rates on dial-up telephone lines. Retrieval of some of these data by telephone is now possible through the University of Southern California. Technological improvements may make this scheme feasible for transmitting large amounts of data. However, for the present, the most practical distribution scheme for time series or spectral data may be to have an online data request facility with the actual data transmission occurring on hard media through conventional mails. It may be useful to retain the telephone line data transmission option, particularly for small data subsets and certain data of particular contemporary interest.

The accessibility of time series or spectral data by investigators can be significantly improved if standard formats can be established for data that are distributed on magnetic tapes. The convenience with which newly acquired data can be combined with existing data sets strongly affects its use. Data formats that are uniform or consistent from agency to agency and earthquake to earthquake significantly increase the value of the data because they can then be used without modifying software to read each new data type.

Development of the needed data-base management systems and improved standards for data dissemination requires appreciable personnel and computer resources. Solutions to these problems can be most efficiently pursued through cooperative efforts among federal, state, and university strong-motion programs. Close cooperation is required to avoid duplication of efforts and to optimize the use of limited personnel resources. A common data-base management system and set of data processing procedures that could be used by all interested programs would not only reduce development and maintenance costs for data management but also permit more efficient use of available resources in data acquisition programs following a major event.

DATA ANALYSIS AND RESEARCH

In the past, emphasis was placed on strengthening the strong-motion instrumentation program through increased installation of instruments in the free-field and in structures. As a result, the data base has grown substantially in recent years. If society is to benefit, however, this enlarged data base must lead to improved earthquake-resistant design and construction. It is important, therefore, that increased emphasis be given to making the data available promptly to users and to expanding the research effort using this data base.

Areas of research that should be emphasized include temporal (time) and spatial variations of the ground motions, design ground motions, seismic hazard analysis, and structural response calculations.

Time Variations

Recorded accelerograms should be used to study three-dimensional strong ground motions at a point characterized through, for example, Fourier spectra, response spectra, correlation functions, cross-correlation functions, probabilistic distributions, mean values, and coefficients of variation. The effects of factors such as source mechanism, site properties and profiles, epicentral distance, focal depth, and magnitude need further clarification.

Spatial Variations

For structures that are large in their horizontal dimensions, e.g., dams, bridges, pipelines, and industrial buildings, the spatial variations of the three-dimensional strong ground motions have a great influence on seismic response, and this is not well understood at present. Furthermore, for deeply embedded structures, such as high-rise buildings and nuclear power plant containment structures, the effects of spatial variations of the three-dimensional strong ground motions with depth are very significant and should be considered in the design of the structure. Yet such spatial variations are not well known. Therefore, it is important that studies be carried out to characterize the spatial variations of ground motions through cross-spectral analyses, multiple-input response spectra, cross-correlation analyses, probability distributions, and other elements. Again, the effects of such factors as source mechanism, site properties and profiles, surface geometry profiles, magnitude, wave types, wave velocities, wave directions, and wave combinations of the motions need clarification.

Design Ground Motions

The seismic design criteria for critical structures must be continually reviewed and updated as new information is gained through studies of strong ground motions. These studies should advance the use of response spectra for three-dimensional ground-motion characterizations. Features needing special attention include spectral shapes, mean values, coefficients of variation, and intensity definitions. The influence of factors such as magnitude, epicentral distance, focal depth, fault type, geology, and site conditions on these features needs study. Also, better definitions of three-dimensional design-accelerograms for time-history analyses are needed regardless of type used, i.e., spectrum-compatible accelerograms, stochastically generated accelerograms, or real measured accelerograms. For use in the design of large structures, phase differences in the accelerograms with distance need clarification and better definition.

Seismic Hazard Analyses

As more strong earthquake ground-motion data are collected, basic studies will provide more realistic modeling as needed in performing seismic hazard analyses, i.e., seismic hazard models reflecting the randomness in space, time, and magnitude of seismic events. Furthermore, magnitude-recurrence, attenuation, rupture-length magnitude, and other relations can be better defined, including the randomness of their parameters. Also, better definitions of effective peak ground acceleration can be developed; they are needed to perform realistic seismic probability risk assessments.

Structural Response Calculations

Strong-motion data have been recently collected on the dynamic response of structures during earthquakes as a result of the placement of instruments. If such information is to be of any value, correlation studies must be carried out to check the validity of mathematical modeling and analysis. Methods of calculating the seismic response of structures must be checked against the actual recorded ground and building motions, otherwise the reliability of methods will not be established.

APPLICATIONS

A comprehensive data bank of strong-motion records, containing statistically significant numbers of events for all site conditions in all seismic regions, would have important applications for improving the safety and economy of engineering installations in seismic regions. Strong-motion data are used in design or evaluation generally in two modes.

1. The availability of large and efficient computing devices has made possible the use of detailed numerical models for determining the earthquake response of specific civil, mechanical, and electrical engineering structures. Such models are especially useful for structures in which failure may threaten many people or may significantly affect the region's economy. Examples are: dams, power plants, power transmission facilities, port facilities, storage facilities for hazardous chemicals, liquefied natural gas and fuel tanks, buildings with sensitive instruments, hospital complexes, industrialized buildings, urban lifelines, offshore platforms, and military installations.
2. Availability of large, strong-motion data banks is also important for developing general design criteria for large classes of buildings and engineering installations. These data would enable the judicious choice of levels of design force and their variations to result in more economical structures without compromising safety.

In earthquake-resistant design, the adequacy of the product depends critically on the quality of the ground-motion estimate, in relation to both the intensity of the shaking and the frequency content. For structures with sensitive response, the result of the analysis will not be any better than the input motion. Improvements in material response models and computational techniques will not improve safety unless the ground-motion estimate is improved.

The information based on strong-motion data is of great value to government agencies concerned with earthquake hazard mitigation, damage assessment, and disaster relief. The information is of particular value to public policymaking agencies.

4

AN INTEGRATED NATIONAL STRONG-MOTION PROGRAM

Strong-motion data increasingly play an important role in earthquake engineering and seismology. They provide the basic information required for understanding the earthquake rupture process, the transmission of seismic energy in the region near the epicenter, the effects of surficial soil topography on the seismic motion, the effects of the strong motion upon structures and their contents, and for the safe and economical design of structures and facilities.

The number of strong-motion instruments in operation in the United States continues to increase, as well as the number and variety of organizations that deploy them. This is indicative of the broad interest in strong-motion data and the various uses to which the data are put. At the present time there is no formal overview of these activities to provide guidance about gaps or overlaps that might exist in strong-motion data gathering, dissemination, and analysis. Because strong-motion activities involve so many organizations there is a need to take a large-scale view of the entire national effort, to identify the strengths and deficiencies, and in particular to identify any critical needs that are not being met. One way of doing this is to consider the elements that make up the national effort.

ELEMENTS OF THE NATIONAL STRONG-MOTION PROGRAM

The U.S. Geological Survey (USGS) operates a national strong-motion network at the federal level. It installs and maintains its own instruments and processes and disseminates the recorded data. It also provides some of these services for other federal agencies having strong-motion programs.

The California Division of Mines and Geology has a large strong-motion program at the state level. It includes the deployment and operation of instruments, the processing of data, and the distribution of data and related information. Publication of data and reports takes place shortly after an earthquake, when the information is of maximum interest to most users.

Universities, industries, various state and local government agencies, building owners, and other entities also acquire strong-motion data, usually for special purposes. Sometimes such data are considered proprietary and are not shared. In other cases the data are made available later, after the principal findings have been published.

An effective national strong-motion program must be concerned with all phases of activities, including strong-motion instrument development, deployment and operation of the instruments, processing, archiving and dissemination of data, the uses of the data, strong-motion research, strong-motion applications, integration of the activities of various governmental agencies, universities and corporations taking part in strong-motion activities, and identification of the amount of funding required for such a national effort and the sources of funding.

INSTRUMENT DEVELOPMENT

Most strong-motion instruments presently installed are the film-recording analog type, with recording initiated at the time that a specified threshold of ground motion is exceeded. The advantages of such instruments are low initial cost and relatively inexpensive maintenance, along with a high likelihood of functioning at the time of an earthquake. Disadvantages are the necessity of digitizing the accelerograms as part of the data processing, missing the portion of the strong-motion record before the recorder is triggered, lack of absolute time marks for identifying wave arrivals, deficiency in high-frequency response, and limited dynamic range.

Digital strong-motion instruments, recording on tape cassettes or disks, are not subject to the limitations of analog instruments. However, at present, they initially are more expensive and less reliable, and their sophistication will likely result in higher maintenance costs.

In balance, however, the advantages of digital over analog recording are such that eventually all strong-motion instruments will be digital. The very quick dissemination of data that is possible with digital accelerographs makes it highly desirable to have at least one installed in each region where significant earthquakes are expected.

There is a need for further development of miniaturized, three-component instruments that can operate in relatively small diameter boreholes in the type of environment encountered at depths of hundreds of meters. There also is a need for direct-recording displacement meters to measure the low-frequency portion of the strong ground motion. These are just two examples of areas of instrument development that might be considered.

There is a need for a plan to upgrade the existing strong-motion installations, considering both the advantages of using state-of-the-art equipment and the added cost of purchase, installation, and maintenance. Priorities need to be established, taking into account the uses to be made of the data, the frequency of occurrence of strong ground motion at particular sites, and the uniqueness of the data to be obtained.

Instrument Deployment and Operation

Plans for deployment of strong-motion instruments require decisions as to whether they should be located in structures or in the free-field. Both kinds of data are needed by engineers, whereas seismologists prefer free-field data. More decisions must be made about the placement of instruments in the structures themselves. In addition, numerous organizations install instruments in special locations for special purposes, but presumably the data obtained would be available to others. A national plan can take into account these sometimes conflicting interests of engineers, seismologists, researchers, and other data users.

Geographic balance consists of more than counting and equalizing the number of accelerographs per square mile, or per thousand population, or per number of earthquakes. For example, large nineteenth century earthquakes in the central and eastern United States caused minor damage at the upper levels of three- and four-story buildings as far away as 700 miles (Dutton, 1890). The upper levels of modern high-rise buildings can be strongly shaken by large earthquakes that are at considerable distances.

Therefore, consideration should be given to instrumenting the basement and upper levels of some high-rise structures in each of the major metropolitan areas east of the Rocky Mountains.

Two- and three-dimensional arrays of strong-motion instruments can provide the data needed to better understand earthquake rupture dynamics and wave transmission as well as effects on structures. Closely spaced instruments in two-dimensional arrays will provide information about wave coherence as a function of wave frequency as well as an explanation of the apparent random character of strong-motion time histories. Three-dimensional arrays will add information about the effects of the physical properties of the transmitting medium (e.g., unconsolidated rock, stiff soil, and hard rock) on the ground motion. Planning should involve considering the advantages of two- and three-dimensional arrays, the desirable locations for the arrays in the United States, and a setting of their priority with respect to other proposed instrument deployments.

The overview of a national strong-motion program should give attention to the adequacy of geographic coverage of strong-motion instruments in the United States. An example of such a plan for the state of California is contained in National Planning Considerations for the Acquisition of Strong Ground-Motion Data (Borcherdt et al., 1984).

Data Archiving and Dissemination

Processing, archiving, and disseminating data are essential parts of strong-motion programs. Considered together, they represent the determining factor as to whether the data will be given application and used. For example, many significant advances in earthquake seismology occurred in the 1960s and later as a direct result of having copies of seismograms from a global network of calibrated instruments collected and available from one source, namely the World-Wide Standardized Seismograph Network. Similar advances can be expected in earthquake engineering and engineering seismology as strong-motion data acquisition is made easier and more convenient.

The form taken by the strong-motion data base should encourage its use by all interested members of the engineering and seismological communities. That is, it should be conveniently accessible so that the investigators can spend their time on analysis and research, rather than in physically acquiring the data and making them compatible with their computing facilities. The data should also be available promptly following a significant earthquake, for this is when interest is at its height.

More attention should be given to the different needs of users as well as changes that might occur in those needs. Certain users may require only values of peak ground motion, along with a copy of an uncorrected accelerogram, within a day or two after the earthquake. Others will want certain processed data on disk or tape, at some later time.

Efficient handling, storage, and retrieval of the large amount of data to be collected on a national basis will necessitate making use of new technology. It is recommended that a strong-motion data center, or centers, be established to publish a catalog of strong-motion data parameters and annual updates of the strong-motion catalog, to archive strong-motion data in a standard format, and to disseminate raw and processed data upon request.

Under the present methods of operation, the recorded strong-motion data do not reach the potential users in a timely manner. This delay is exacerbated by the many uncoordinated instrument installations. Furthermore, users generally feel that even the data of the USGS and the California State strong-motion programs do not become easily and quickly available.

This problem is being addressed by the California Seismic Safety Commission which has established the Data Utilization Committee to advise the state strong-motion program on expediting the availability of data and encouraging a wider use of the data. The USGS now sends its data to the National Geophysical Data Center (NGDC) in Boulder for archiving and disseminating, but it appears that the NGDC service may no longer be available and another procedure will be needed. The panel feels that the proposed Joint Subcommittee on the U.S. Strong-Motion Program (see Recommendation No. 1) should, as one of its first tasks, review the California State program, the USGS program, and the NGDC operation and make recommendations on the dissemination and utilization of strong-motion data that will lead to greater use.

Strong-Motion Research

Research activities are usually determined by the interests of the individual investigators and they are continually subject to change, depending on accomplishments, perceived needs, and availability of support. Continuous review is needed to highlight both the accomplishments and needs, as well as those areas of research with a high potential for success.

Such review also will point out imbalances or deficiencies that may exist in the total national research effort, such as lack of funding for continued research after data are acquired, unavailability of the National Science Foundation (NSF) Science Directorate support for individuals or universities desiring to understand strong-motion research, lack of an external research program on strong ground motion in the USGS, possible duplication of efforts by various organizations in some geographic areas, and possible neglect of other areas that deserve study.

Strong-motion data will be more widely used as they become readily available in a uniform and user-friendly format. The number of people who use the data for research and application also can be expected to increase, particularly if financial support for such activity increases. Guidelines are needed as to the amount of support required for the analysis of existing data bases; such support has been inadequate in the past.

The NSF Engineering Directorate plays the lead role in research funding of strong motion studies for earthquake engineering purposes. The USGS also carries out research in strong motion, but such research is confined to its internal program. Many of the other federal agencies concerned with earthquakes, although primarily mission oriented, have need for research on specific aspects of the subject. This is particularly true of the regulatory agencies. Their requirements or needs should be identified along with methods of making research funds available.

Coordination of Strong-Motion Activities

There always will be some military or industrial needs for strong-motion data that require the data to be exclusive property. These, however, should be a small percentage of the total amount of data acquired. Researchers at universities and in government agencies cannot claim the right to exclusive use of data acquired by them when the support for both operation of instruments and for the research comes from tax money. Therefore, the great majority of strong-motion data should be made available to all interested parties as soon as possible. When a university or government organization receives research support for strong-motion data acquisition, it should be with the understanding that the organization accepts the responsibility to make the data available to those who request it. To minimize the effort involved, this can best be accomplished by submitting it to a single collection organization, which has the responsibility to disseminate expeditiously and archive the data.

However, coordination of strong-motion activities involves more than sharing data. In some cases there might be redundancy among agencies in operation, research, and applications. Even worse, there may be geographic areas or particular topics in research and application that should have a high priority but have been overlooked or are not being addressed. Continuing review of the U.S. strong-motion plan will note such inequities and make recommendations to rectify any imbalances that exist. A more efficient and productive national effort will result from the coordination of the programs of federal, state, and local governmental agencies and others.

The common interests and goals of the members of the engineering and seismological communities must be emphasized to produce cooperation rather than unproductive competition. Although the various agencies (e.g., USGS, NSF--Engineering, NSF--Earth Sciences, and state programs) often discuss matters of mutual interest on an ad hoc basis, there is no formal procedure for doing so. The same is also true of the coordination of the various program elements of universities, government agencies, and private corporations.

Funding of Strong-Motion Activities

To a certain extent the development and funding of the strong-motion program have been evolutionary as a result of many factors, including requirements to meet special needs. For example, following the 1971 San Fernando (California) earthquake which seriously damaged hospitals and dams, the Veterans Administration placed strong-motion instruments at all of their hospitals in seismic zone 2 or higher, the U.S. Army Corps of Engineers and the Bureau of Reclamation installed instruments at dams in earthquake-active regions, and the Nuclear Regulatory Commission provided support for strong-motion instruments in central and eastern North America, where the majority of nuclear power plants are located.

There is a need to identify all the governmental agencies and private organizations having an interest in the operation of strong-motion instruments, in research, and in the application of strong-motion data and research. By considering the integrated needs in a national strong-motion program, a better balance will be achieved with regard to the amount and type of support that each of the agencies and organizations will be expected to contribute. This will have the additional advantage of providing more rational choices in the preparation of budgets, which are made years in advance of actual commitments.

Funding considerations for the national effort should take the broad perspective. They need not be concerned with budgetary details, but should present overall dollar needs (with options) and a breakdown into large categories, along with the names of agencies that logically can be expected to provide the support in each of the categories. Such a plan will provide a realistic assessment of all the money that is spent on strong-motion activities in the country.

MECHANISMS FOR ONGOING PLANNING AND COORDINATION

This report of the Panel on Strong Motion Instrumentation presents an evaluation of the current status of strong-motion activities and needs for the immediate future. In such a dynamic and rapidly evolving area, continuous oversight and updating are required, especially in instrument development, data processing management and dissemination, and research developments, in order to understand the physics of the earthquake rupture process, the effects of the radiated waves on the motion of the ground, and the response of structure to ground motions.

The panel, accordingly, recommends that the Committee on Earthquake Engineering and the Committee on Seismology of the National Research Council establish a continuing joint subcommittee on the U.S. Strong-Motion Program. The responsibilities and activities of this proposed subcommittee are presented in "Overview and Recommendations" along with other recommendations.

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APPENDIX: SUMMARY OF STRONG-MOTION INSTRUMENTATION EFFORTS IN THE UNITED STATES

A more detailed listing of organizations and instruments is given in the report of the Santa Barbara Workshop (Iwan, 1981).

Organization	Number of Instruments
California Division of Mines and Geology	500
U.S. Army Corps of Engineers	350
U.S. Geological Survey	275
Pacific Gas and Electric Company	91
State of Washington	90
University of Southern California	81
Department of Energy	80
Bureau of Reclamation	70
Veterans Administration	65
Nuclear power plants	62
California Department of Water Resources	70
University of California, Los Angeles	36
Los Angeles Department of Water and Power	35
U.S. Navy	35
Federal Highway Administration	30
Metropolitan Water District of Southern California	30
Southern California Edison Company	26
Los Angeles Flood Control District	25
University of California, San Diego	21
International Business Machines Company	20
Columbia University	18
Stanford University	15
California Institute of Technology	15
Washington Department of Transportation	15
Idaho National Engineering Laboratory	15
Lawrence Livermore National Laboratory	15
Buildings instrumented in cities using Uniform Building Code	321
Instruments installed by various organizations	325
The City of Los Angeles requires owners of large buildings to install and maintain strong-motion instruments. This is the largest uncoordinated collection of instruments.	500