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A WORKSHOP ON "EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE HAZARDS REDUCTION IN THE CENTRAL UNITED STATES"

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Reston, Virginia

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DEDICATION

When questions are raised about earthquake hazards in the Eastern United States and ways are sought to mitigate their effects, the inquirer is inevitably lead to Dr. Otto W. Nuttli, Professor of Geophysics at St. Louis University. Otto, as he is known to his many acquaintances, friends, students, colleagues, and professional associates throughout the Nation, not only has contributed substantially through his research to the understanding of earthquake hazards in the New Madrid seismic zone, in the Charleston, South Carolina area, and in the Northeastern United States, but he has also invested considerable time and energy in speaking out on behalf of increased earthquake preparedness. He has contributed significantly to the expansion of knowledge about earthquakes and the increase in commitment to mitigate their effects.

This report, the proceedings of the workshop on "Earth Science Considerations for Earthquake Hazards Reduction in the Central United States," is dedicated to Dr. Otto W. Nuttli as a token of our appreciation for his tireless efforts in the National Earthquake Hazards Reduction Program. His numerous contributions have provided a sound technical basis for continuing sustained efforts to increase earthquake preparedness in the Eastern United States.

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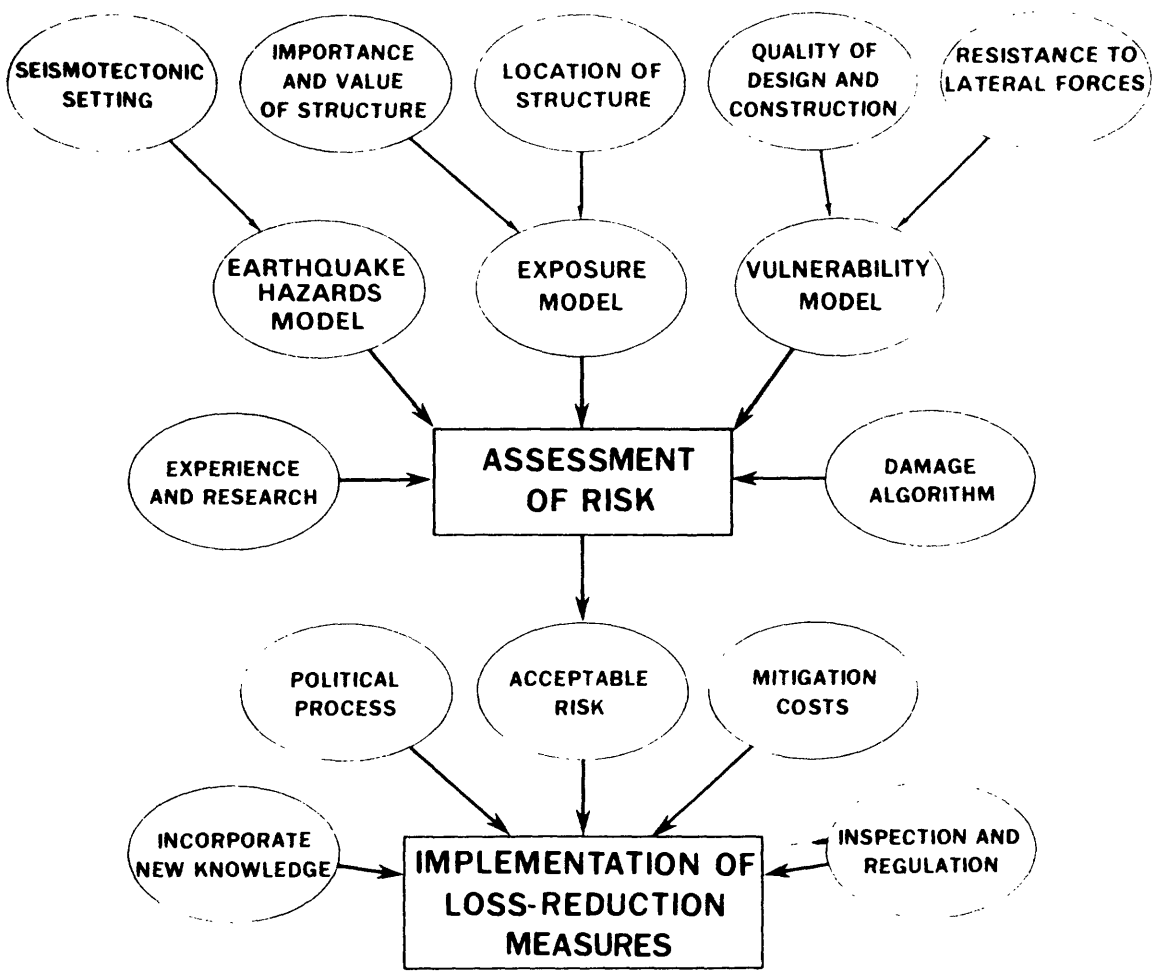
PREFACE

The workshop on "Earth Science Considerations for Earthquake Hazards Reduction in the Central United States" was convened by the U.S. Geological Survey and the Federal Emergency Management Agency to strengthen research and mitigation activities in the Central United States. These activities, shown schematically in the figure below, depend on the use of existing geologic, seismological, and engineering data, augmented as necessary with new data acquisition programs to close specific gaps in technical knowledge. The critical questions in the Central United States are:

1) Which loss-reduction measures can be implemented partially or completely now with the existing data bases?
2) Which loss-reduction measures require additional data acquisition programs for complete implementation?
3) What obstacles are now preventing implementation?
4) How can these obstacles be overcome?



Schematic illustration of the overall process involved in the assessment of earthquake hazards and risk in the Central United States. The models for earthquake hazards, exposure, and vulnerability are critically important parts of the total process that leads to implementation of loss-reduction measures.

In the Central United States, time is both an ally and an enemy. As an ally, great earthquakes such as the 1811-1812 sequence are such rare events that they allow man to make mistakes in earthquake-resistant design without being penalized very often. As an enemy, man is lulled into apathy, thinking that there is no urgency for mitigating the potential losses from earthquakes that will recur, but in the distant future. The Central United States Earthquake Consortium (CUSEC) formed by the Federal Emergency Management Agency in FY 1983, has major responsibilities for improving earthquake preparedness in the Central United States. To carry out its responsibilities, CUSEC must answer questions like those above and others and provide leadership for carrying out a wide variety of short- and long-term activities which are identified in this report.

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BACKGROUND AND SUMMARY OF THE WORKSHOP ON "EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE HAZARDS REDUCTION IN THE CENTRAL UNITED STATES"

by

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INTRODUCTION

Seventy-six earth scientists, engineers, planners, and emergency management specialists participated in a 2-day workshop on "Earth Science Considerations for Earthquake Hazards Reduction in the Central United States." The workshop, convened under the auspices of the National Earthquake Hazards Reduction Program (NEHRP), was held in Nashville, Tennessee, on March 25-26, 1986--175 years after the occurrence of the first of the great earthquakes in the sequence that occurred in the New Madrid seismic zone in the winter of 1811-1812. The sponsors of the workshop were the Central United States Earthquake Consortium (CUSEC), Tennessee Emergency Management Agency (TEMA), Federal Emergency Management Agency (FEMA), and U.S. Geological Survey (USGS).

This workshop was the thirty-fifth in a series of workshops and conferences that the USGS has sponsored since 1977, usually in cooperation with FEMA, the lead agency in the NEHRP. Each past workshop sponsored by USGS and FEMA had a general goal of bringing together participants having experience in the production and use of knowledge of the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, regional tectonic deformation, and where applicable, tsunamis and seiches. In addition, each past workshop had a general goal of strengthening new and ongoing activities in the State or region to mitigate losses from earthquake hazards. The goals of this workshop were the same as in the past, but they also included the following specific goals:

-- Provide participants with current knowledge of the earthquake hazards of ground shaking, surface fault rupture, and earthquake-induced ground failure in the Central United States.

-- Provide participants with publications containing guidelines for earthquake hazards reduction developed in the past several years by FEMA as part of their programs to aid State and local governments.

-- Describe how the body of existing technical data and knowledge is being applied (or could be applied) to devise loss-reduction measures at Federal, State, and community levels in the Central United States.

-- Accelerate research in the universities and private sector to close specific gaps in knowledge.

-- Foster the development and implementation of loss-reduction measures through CUSEC, a principal part of the Central United States Earthquake Preparedness Project (CUSEPP).

Since 1981, four prior workshops in the Central United States have been sponsored by USGS, FEMA, and other agencies and institutions to improve earthquake preparedness. They were:

-- Conference XV, A workshop on "Preparing for and Responding to a Damaging Earthquake in the Eastern United States," September 16-18, 1981, Knoxville, Tennessee (U.S. Geological Survey Open-File Report 82-220).

-- Conference XVIII, A workshop on "Continuing Actions to Reduce Losses from Earthquakes in the Mississippi Valley," May 24-26, 1982, St. Louis, Missouri (U.S. Geological Survey Open-File Report 83-157).

-- Conference XXIII, A workshop on "Continuing Actions to Reduce Potential Losses from Future Earthquakes in Arkansas and Nearby States," September 20-22, 1983, North Little Rock, Arkansas (U.S. Geological Survey Open-File Report 83-846).

-- Symposium on "The New Madrid Seismic Zone," November 26, 1984, (U.S. Geological Survey Open-File Report 84-770).

ISSUES ASSOCIATED WITH THE IMPLEMENTATION OF LOSS-REDUCTION MEASURES

Information and experience gained by USGS, FEMA, National Science Foundation, and National Bureau of Standards since 1977 in the NEHRP have shown that the implementation process is as complex as any research study. In each earthquake-prone region of the Nation, two principal issues impact implementation. They are:

-- Will implementation of loss-reduction measures happen without the occurrence of a major earthquake (Figure 1)?

-- How much more will loss-reduction measures cost and where will the required money come from--from reprogramming or from new sources?

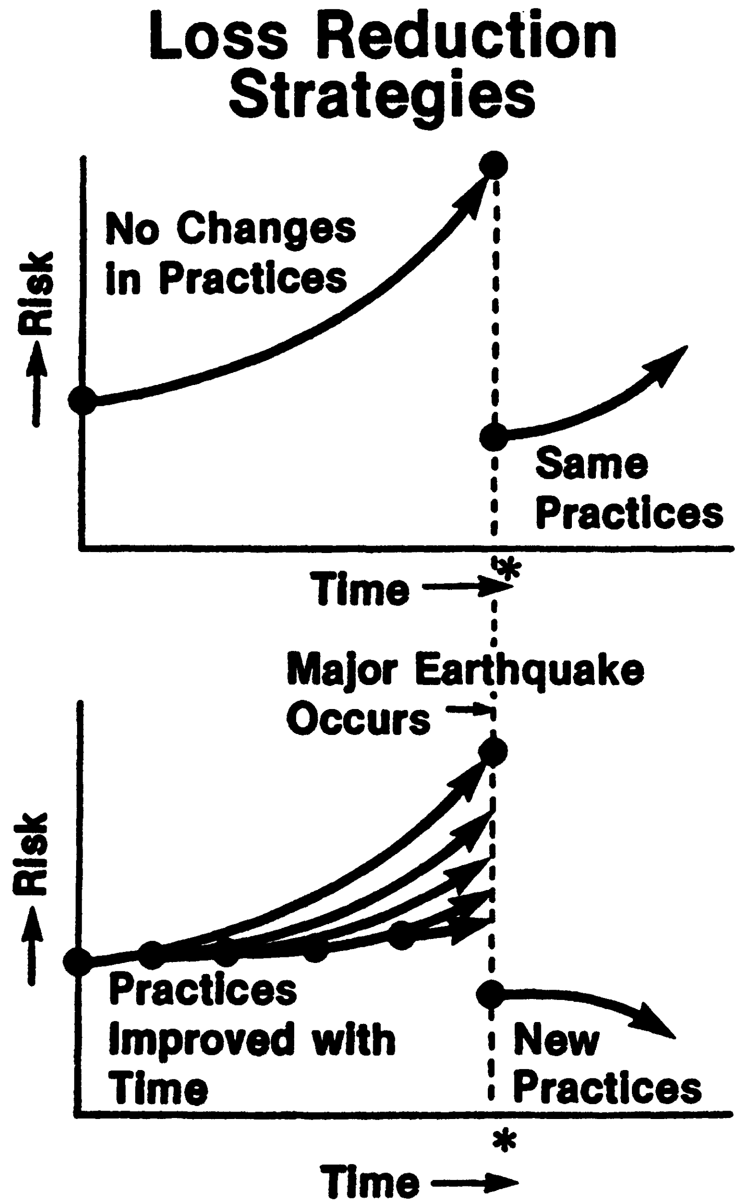
Experience in the NEHRP shows that implementation of loss-reduction measures tends to happen when 5 critical interrelated elements are present (Figure 2). Each element is described below.

Element 1: Existence of a Technical Data Base--Effective implementation requires explicit knowledge of the nature and extent of the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, and regional tectonic deformation in the urban area (Figure 3). The quantity and quality of the geologic, seismological, and engineering data are the two most important factors that facilitate making assessments of the earthquake hazards and risk and devising and implementing loss-reduction measures.

Using the definition that an issue is defined as a question for which except opinion is divided between "yes" and "no," the critical issues of implementation that are directly related to the technical data bases are:

-- Can the existing data be utilized to foster implementation of loss-reduction measures or must the data be translated, extrapolated, or augmented?

-- Do we have enough data for implementation of loss-reduction measures?



Figures 1. Schematic illustration of the critical issue in the implementation process. "Will significant implementation of loss reduction measures take place in the central United States without a major earthquake?"

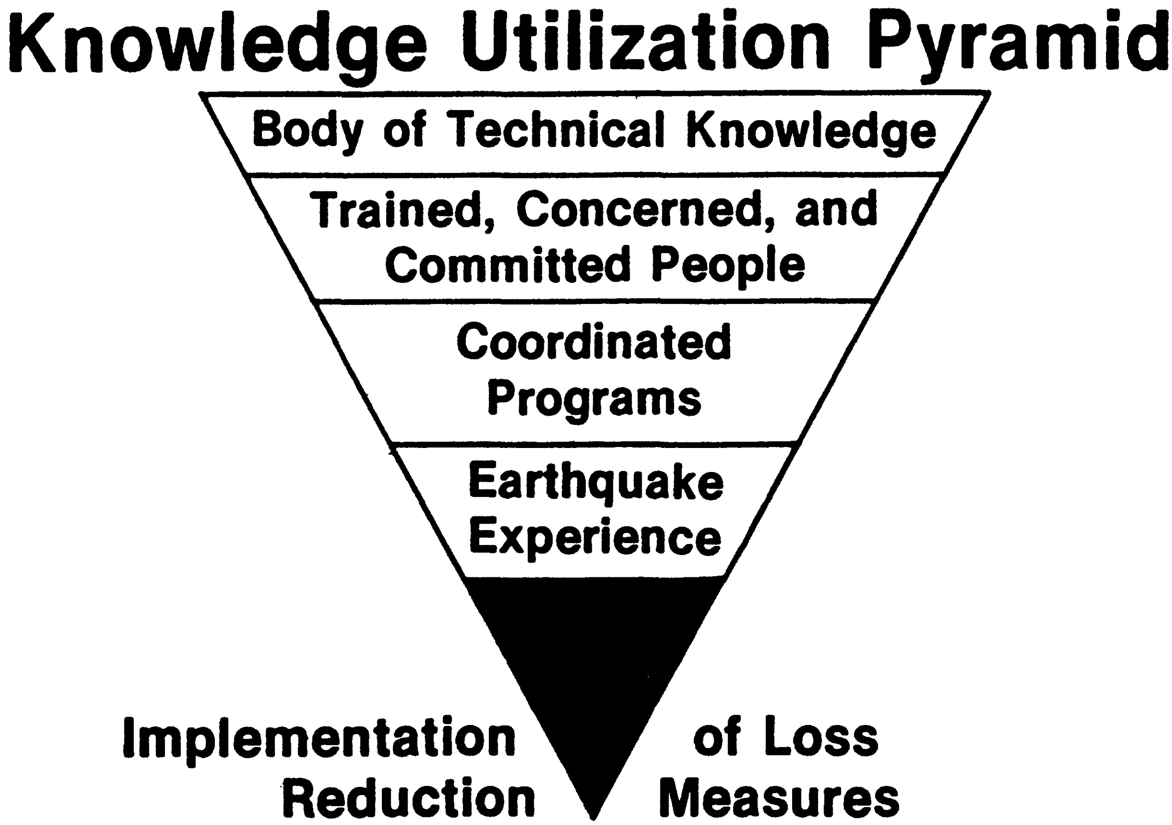


Figure 2. Schematic illustration of the five critical elements of the earthquake-hazards-reduction implementation process. The flow is from top to bottom. All elements seem to be needed to ensure success.

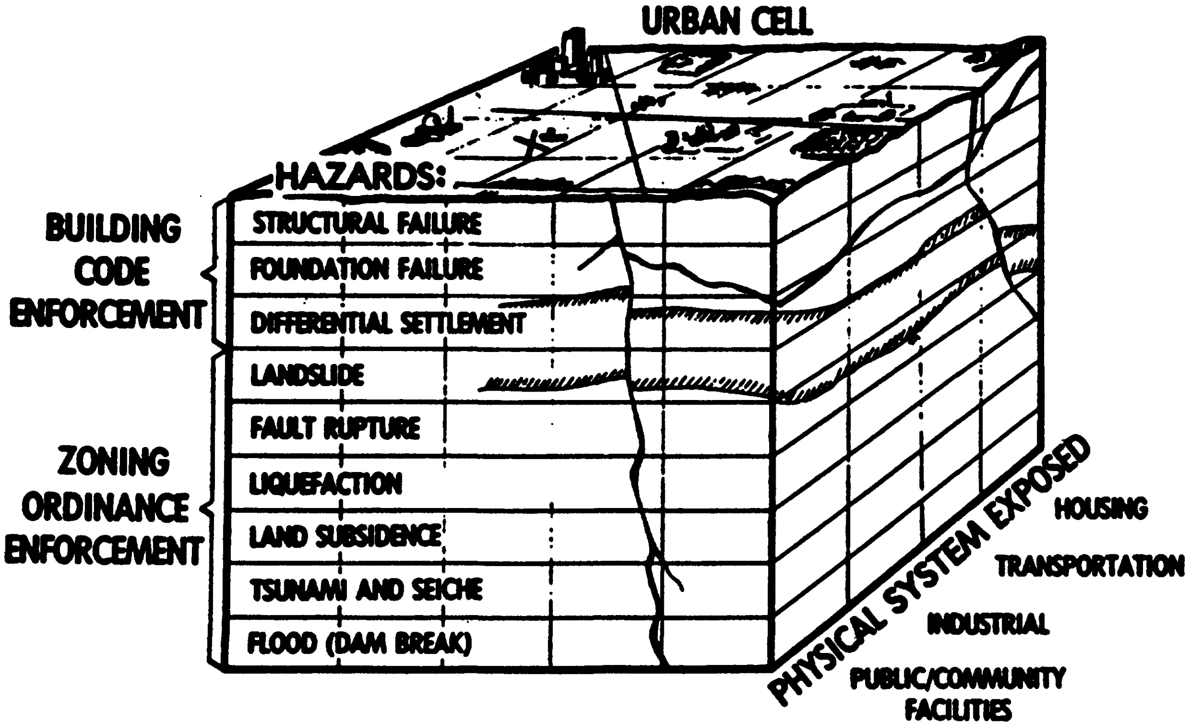


Figure 3. Schematic illustration of a community facing potential losses from the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, and regional tectonic deformation. The community has the capability to implement a wide range of loss-reduction measures to minimize the potential impacts. Decisionmakers in the community must decide which loss-reduction measures are most cost effective and take the lead in implementing them.

-- Are the data at the right scale?

-- Can we extrapolate beyond the limitations of the technical data bases to address specific requirements of users in a reasonable, yet conservative manner?

Technical data are required on three scales:

-- global (map scale of about 1:7,500,000 or larger) to give the "big picture" of the inter- and intraplate forces.

-- regional (map scale of about 1:250,000 or larger) to define the physical parameters and their range of values that provide a framework of understanding of the spatial and temporal characteristics of earthquake hazards in a region.

-- local (map scale of about 1:24,000 or smaller) to determine the physical parameters and their range of values that control the local earthquake-resistant design requirements. Site-specific design requirements are not covered by this scale; they are based on site-specific data.

The available data must be integrated and analyzed, quantifying uncertainty as appropriate, to obtain explicit answers to the questions:

-- Where have earthquakes occurred in the past? Where are they occurring now?

-- How big in terms of epicentral intensity and/or magnitude were the past earthquakes? How big can future earthquakes be? Has the maximum magnitude earthquake ever occurred?

-- What physical effects (hazards) have past earthquakes caused? What was their extent spatially and temporally? What was their level of severity?

-- What were the causative mechanisms for each earthquake? Each hazard?

-- How often (on the average) do earthquakes of a given magnitude (or epicentral intensity) occur? How often on the average, does ground shaking of a certain level occur?

-- What are the viable options for mitigating the earthquake hazards expected to occur in the region in a 50 year exposure time (the useful life of ordinary buildings).

Element 2: Trained, Concerned, and Committed People--Trained people are required to analyze the technical data bases, to extrapolate beyond the limits of the data, and to translate the basic data into maps and other products so that practical and reasonable loss-reduction measures can be devised. The critical issues of implementation that are directly related to people are:

-- Is appropriate training available to transfer the state-of-the-art and the state-of-practice to professionals?

-- Can people who have never experienced a damaging earthquake be motivated to have increased concern about earthquakes and their effects?

-- Can people who have been uncommitted with respect to implementation of loss-reduction measures be transformed into people who are committed to provide leadership for changing the "status quo" of implementation?

The people who make the implementation process happen must deal with a wide range of geologic, seismological, and engineering seismology data and produce credible, practical loss-reduction measures. To succeed, they must know that there are differences in the perspectives of scientists/engineers and decisionmakers (described in Table 1) and have experience in minimizing these differences.

Table I

Differences in the perspectives of scientists/engineers and decisionmakers (from Szanton, 1981).

Attributes	Perspectives	
	Scientists/Engineers	Decisionmaker
1. Ultimate objective	Respect of Peers	Approval of electorate
2. Time horizon	Long	Short
3. Focus	Internal logic of the problem	External logic of the problem
4. Mode of though	Inductive, generic	Deductive, particular
5. Most valued outcome	Original insight	Reliable solution
6. Mode of expression	Abstruse, qualified	Simple, absolute
7. Preferred form of	Multiple possibilities with conclusion	One "best" solution uncertainties emphasized with uncertainties submerged

Element 3: Programs--The data, information, and people provide the resource base for programs such as: research studies; the assessment of earthquake hazards, vulnerability, and risk for specific urban areas; a seismic safety organization; mitigation and preparedness actions; and the implementation of new and improved loss-reduction measures. The success of each program depends on: how well it is focused, how well it is integrated, and how well it is coordinated between the various disciplines and agencies. The critical issues of implementation that are directly associated with programs are:

-- Do the expected benefits justify the cost and the anguish associated with reallocation of resources?

-- Are the technological, societal, and political considerations appropriately balanced?

-- Does the program have a definite ending point; if not, should it? Can the end point be negotiated before the program begins?

Element 4: A Damaging Earthquake--A damaging earthquake provides the best opportunity to acquire unique geologic, seismological, engineering, and social science information and to foster implementation of specific loss-reduction measures in a community. The critical issues of implementation that are directly related to the occurrence of a damaging earthquake are:

-- Does the earthquake provide relevant information for stimulating earthquake preparedness in the community?
-- Can useful "lessons" be extracted from the earthquake experience?

The following types of investigations are typically conducted after a damaging earthquake and provide a rapid way of infusing new data and knowledge (Hays, 1986).

-- Geologic studies--field investigations to determine the nature, degree, and spatial distribution of surface faulting, regional tectonic deformation, landslides, liquefaction, and wave inundation from seiches, and tsunamis.

-- Seismological studies--measurement programs using arrays of portable seismographs to locate earthquakes comprising the aftershock sequence, to define the spatial extent of the fault rupture zone and its temporal changes, and to determine the focal mechanisms of the earthquake.

-- Engineering Seismology Studies--measurement programs using arrays of portable strong motion accelerographs and broad band seismographs to measure the characteristics of strong ground motion at various epicentral locations underlain by various soil-rock columns, using both the main shock and the aftershock sequence.

-- Engineering Studies--Investigations on a building-by-building scale to determine the nature, degree, and spatial distribution of damage to a wide range of structures, including: low-, medium-, and high-rise buildings, lifelines, and critical facilities.

-- Societal Studies--Investigations to determine how the populace reacts before, during, and after an earthquake and to devise ways the new technical information can be transformed into public policy and new or improved loss-reduction measures.

When a long time has elapsed since the last historic damaging earthquake (e.g., such as in the Mississippi Valley) or no historic earthquake has occurred (e.g., such as along the Wasatch front, Utah), a scenario earthquake can be used to foster the implementation process by heightening awareness and concern. The main issues associated with scenario earthquakes are:

-- Is the scenario earthquake sufficiently credible in terms of present knowledge that it will be used to guide the development of the community's response plans?

-- Is the scenario earthquake realistic in terms of the actual geologic setting of the community and the social and political conditions in the community and, if so, will it be used as the basis for specific mitigation activities?

Element 5: Loss Reduction Measures--A wide range of practical loss-reduction measures are now available for implementation in a community. The overriding issue of implementation that is directly related to each loss-reduction measure being considered is:

-- How much more does the loss-reduction measure cost in comparison with the cost of maintaining the "status quo?"

Loss-reduction measures can be grouped in the following categories:

-- Hazard maps - Maps showing the relative severity and spatial variation of a specific hazard (for example, the ground-shaking hazard) that can be used in applications ranging from design guidelines to seismic microzoning to regulations.

-- <u>Design criteria</u> - Criteria for siting a wide range of structures (including those covered by building codes as well as by other regulations), such as: public buildings, schools, private buildings, critical public facilities, dams, hospitals, and nuclear power plants.

-- <u>Guidelines and regulations</u> - Guidance for regional and urban planning to improve land-use in the context of earthquake hazards.

-- <u>Seismic microzoning</u> - A procedure that utilizes the existing technical data as a basis for the division of a region into zones expected to experience the same relative severity of a specific earthquake hazard in a given exposure time (such as the level of ground shaking expected in a 50 year period).

Seismic microzoning provides the prospective user of an area with the design criteria that will permit him to select the most suitable part of the area for the proposed use.

-- <u>Inspection and review</u> - Procedures to regulate design and construction, practices.

-- <u>Public policy</u> - Policies that lead to improved seismic safety.

-- <u>Education and training</u> - Short- and long-term activities designed to close specific gaps in knowledge. Training prepares people to do a wider variety of tasks than they could do without training.

-- <u>Response planning</u> - Planning that improves the capability of the region and state to respond effectively to a damaging earthquake.

FEMA'S EARTHQUAKE HAZARDS REDUCTION PUBLICATIONS

Since 1985, FEMA has developed the Earthquake Hazards Reduction Series to assist State and local governments in their efforts to improve earthquake preparedness, response, and mitigation. These publications have been widely disseminated at conferences, workshops, and through mailings. They are available from FEMA headquarters in Washington, D.C.. They are comprehensive in scope and include the following titles:

-- Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide, Earthquake Hazards Reduction Series 1 (1985).

-- Comprehensive Earthquake Preparedness Planning Guidelines: City, Earthquake Hazards Reduction Series 2 (1985).

-- Comprehensive Earthquake Preparedness Planning Guidelines: County, Earthquake Hazards Reduction Series 3 (1985).

-- Comprehensive Earthquake Preparedness Planning Guidelines: Corporate, Earthquake Hazards Reduction Series 4 (1985).

-- Earthquake Preparedness Information for People with Disabilities: Earthquake Hazards Reduction Series 5 (1985).

-- Pilot Project for Earthquake Hazard Assessment, Earthquake Hazards Reduction Series 6 (1985).

-- Earthquake Insurance: A Public Policy Dilemma, Earthquake Hazards Reduction Series 7 (1985).

-- Earthquake Public Information Materials: An Annotated Bibliography, Earthquake Hazards Reduction Series 8 (1985).

-- Societal Implications: A Community Handbook, Earthquake Hazards Reduction Series 13 (1985).

-- Societal Implications: Selected Readings, Earthquake Hazards Reduction Series 14 (1985).

-- Proceedings: Workshop on Reducing Seismic Hazards to Existing Buildings, Earthquake Hazards Reduction Series 15 (1985).

-- An Action Plan for Reducing Earthquake Hazards of Existing Buildings, Earthquake Hazards Reduction Series 16 (1985).

-- NEHRP Recommended Provisions fro the Development of Seismic Regulations for New Buildings: Part 1: Provisions and Part 2: Commentary: Earthquake Hazards Reduction Series 17 and 18 (1986).

-- State and Local Earthquake Hazards Reduction: Implementation of FEMA Funding and Support, Civil Preparedness Guide 2 (1985).

THE NEW MADRID SEISMIC ZONE

Sir Charles Lyell (1849) gave the earliest geologic description of the New Madrid earthquakes, the 3 great earthquakes that struck the New Madrid, Missouri area in the winter of 1811-1812. One hundred years after the earthquakes, Fuller (1912) proposed reasonable explanations for physical phenomena associated with the earthquakes, suggesting faulting of hard Paleozoic rocks as the probable explanation. He also recognized that most of the disturbance from these earthquakes occurred in a linear zone, a fact that was later proven in the 1960's and 1970's by integration of gravity, magnetic, seismic, geologic mapping and paleoseismicity research studies. From all of these observations, the concept of the New Madrid seismic zone emerged--a complex structural framework. This concept is now being used in the assessment of earthquake hazards and risk in the Central United States.

More than 100 years of accumulated knowledge provide the following facts about the New Madrid seismic zone (McKeown and Pakiser, 1982).

-- The New Madrid seismic zone is a buried rift-type zone in the upper Mississippi embayment about 70 km wide, more than 200 km long, and having 2 to 3 km of structural relief.

-- More than 90 percent of the present-day seismicity in the region occurs along a linear axial zone within the rift zone.

-- Geomorphic studies indicate Holocene (10,000 years before the present) uplift and faulting in the Reelfoot Lake area, Tennessee.

-- An average recurrence interval of about 600 years is indicated from paleoseismicity studies in the Reelfoot Lake area for earthquakes large enough to produce ground motion having sufficient strength to cause liquefaction. The recurrence interval of 600 years has an unknown level of uncertainty.

THE 31 JANUARY 1986, CLEVELAND, OHIO, EARTHQUAKE

As a reminder that it is not a question of if but rather when the next damaging earthquake will recur in the Central United States, a small earthquake (m_b = 5.0) occurred on January 31, 1986. The epicenter was about 50 km (30 mi) northeast of Cleveland, Ohio. The focal depth was uncertain, but was estimated to be shallow, about 2 to 7 km (1 to 4 mi). The earthquake was recorded on a strong motion instrument located at the Perry nuclear plant, 17 km (10 mi) from the epicenter. The recorded levels of ground motion, which exceeded the design levels of the safe shutdown earthquake, were:

-- 0.18 g north-south component.
-- 0.11 g east-west component.
-- 0.10 g vertical component.

The values of spectral velocity exceeded the design response spectrum in the vicinity of 20 Hz., reaching 1 to 2 in/sec. for 2% damping.

As in past earthquakes in the Central United States, the outstanding feature of the 1986 Cleveland earthquake was the large felt area. The earthquake was felt strongly as far away as Washington, D.C.

THE 19 SEPTEMBER 1985 MEXICO EARTHQUAKE

Although the seismotectonic regimes are different in the Central United States (an intraplate rift zone where great earthquakes occur about once every 600-1000 years) and in Mexico (an interplate zone of thrust faulting where the Nazca tectonic plate is being subducted beneath the North American plate and large-to-great earthquakes occur one or more times each century), the Mexico earthquake provided new knowledge having value for research and response planning in the Central United States. The Mexico earthquake reminded the earthquake engineering community of the world that:

-- Earthquakes tend to recur where they occurred in the past, on faults that have a lifecycle and an average recurrence interval for earthquakes of various magnitudes. Earthquakes also fill seismic gaps along the boundaries of major tectonic plates.

-- Site amplification of a factor of 5 or more can occur under conditions of low to intermediate levels of shear strain and low peak ground accelerations. This phenomenon can occur at sites underlain by soft soil located as far away as 400 km (250 mi) from the epicenter.

-- Soil-structure interaction leading to severe damage and collapse of buildings can occur when the dominant period of the rock motion is the same as the dominant periods of the response of the soil column and the response of the building.

-- If the state-of-earthquake-preparedness and mitigation actions in an urban area before a damaging earthquake are advanced, a damaging earthquake need not be a disaster.

EARTHQUAKE HAZARDS IN THE CENTRAL UNITED STATES

All of the physical effects (hazards) described in this section can occur in the Central United States. The description below places some upper bounds on what will happen when a large (magnitudes of 7 to 8) or great (magnitudes of 8 and larger) earthquake recurs.

The sudden abrupt release of slowly accumulating strain energy, usually occurring within a few cubic kilometers (miles) of the Earth's crust, produces mechanical energy that is propagated in the form of seismic waves which radiate from the earthquake focus in all directions through the Earth. When the energy of the high-frequency (short-period) body waves (P and S waves) arrives at the surface of the Earth, secondary surface waves having low frequencies (long periods) are formed. The frequency and amplitude of the vibrations produced at points on the Earth's surface (and hence the severity of the earthquake) depend on the amount of mechanical energy released at the earthquake focus, the distance and depth of the focus relative to the point of observation, and the physical properties of the rock or soil on or near the surface of the Earth at the point of observation.

Effects--A great earthquake (magnitudes of 8 and larger), such as each of the three earthquakes that occurred in New Madrid in 1811-1812, is one of nature's most devastating phenomena causing considerable damage and loss in a matter of 2 to 3 minutes (Figure 4). The onset of a great earthquake is initially signaled by a deep rumbling sound or by disturbed air making a rushing sound, followed shortly by a series of violent motions of the ground. The surroundings seem to disintegrate. Often the ground fissures with large permanent displacements--21 feet horizontally in San Francisco in 1906 and 47 feet vertically at Yakutat Bay, Alaska in 1899. Buildings, bridges, dams, tunnels, or other rigid structures are sheared in two or collapse when subjected to this permanent displacement.

Ground vibrations can exceed the force of gravity (980 cm/sec/sec) and be so severe that large trees are snapped off or uprooted (Figure 5). People standing have been knocked down and their legs broken by the sudden horizontal ground accelerations that are more damaging to buildings than vertical ground accelerations.

As the ground vibrations continue, structures having different frequency-response characteristics begin to vibrate. Sometimes resonate vibrations result. The resonance effect is particularly destructive, since the amplitude of the vibration increases (theoretically without limits) and usually causes structural failure. Adjacent buildings having different frequencies of response can vibrate out of phase and pound each other to pieces (as in the 1985 Mexico earthquakes). In any case, if the elastic strength of the structure is exceeded, cracking, spalling, and--often--complete collapse results. Chimneys, high-rise buildings, waste tanks, and bridges are especially vulnerable to long-period vibrations; whereas, low-rise buildings are especially vulnerable to short-period vibrations. The walls of high-rise buildings without adequate lateral bracking frequently

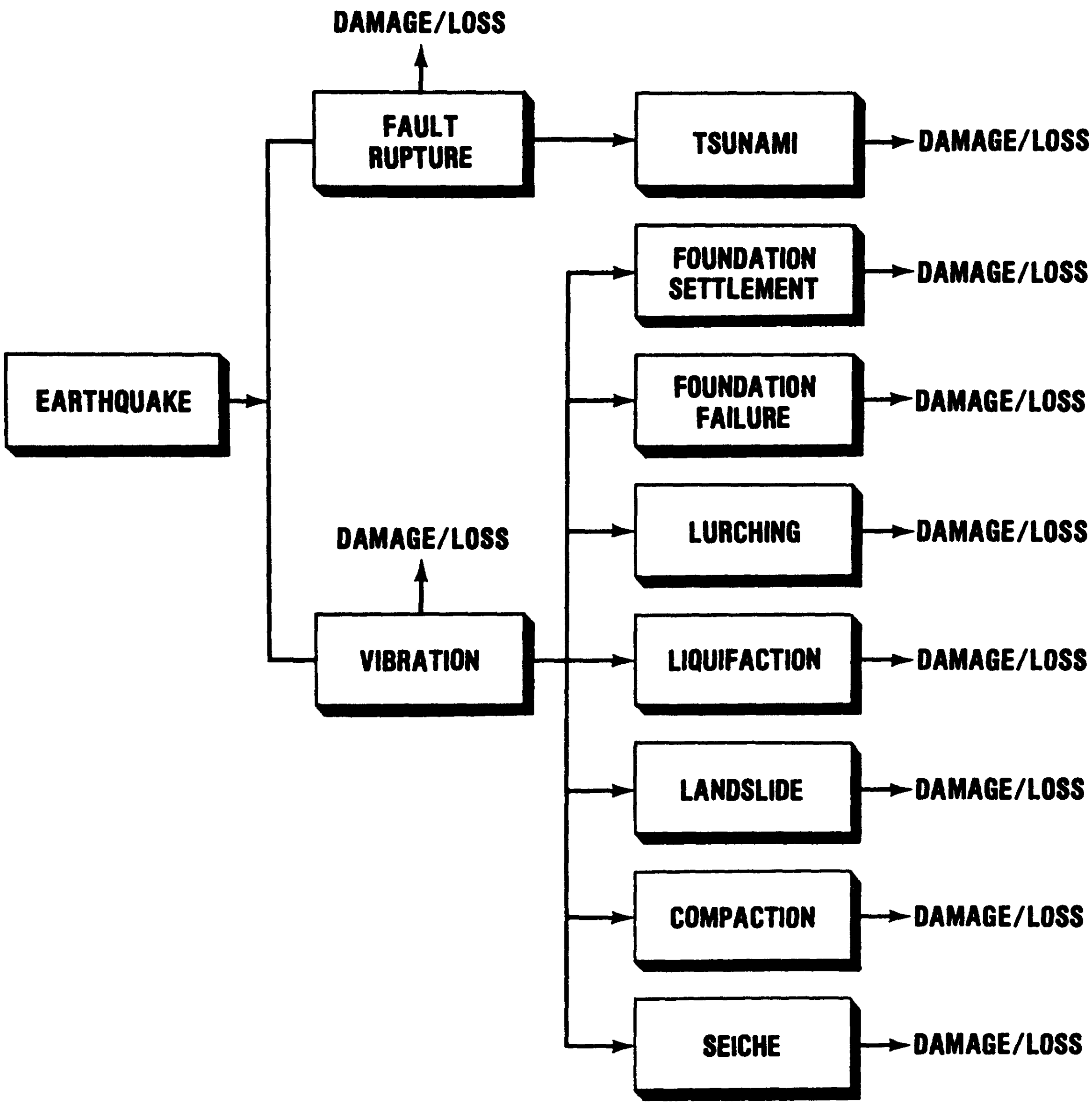


Figure 4. Schematic illustration of the physical effects that are generated by an earthquake. These physical effects cause socio-economic losses unless steps are taken to mitigate them.

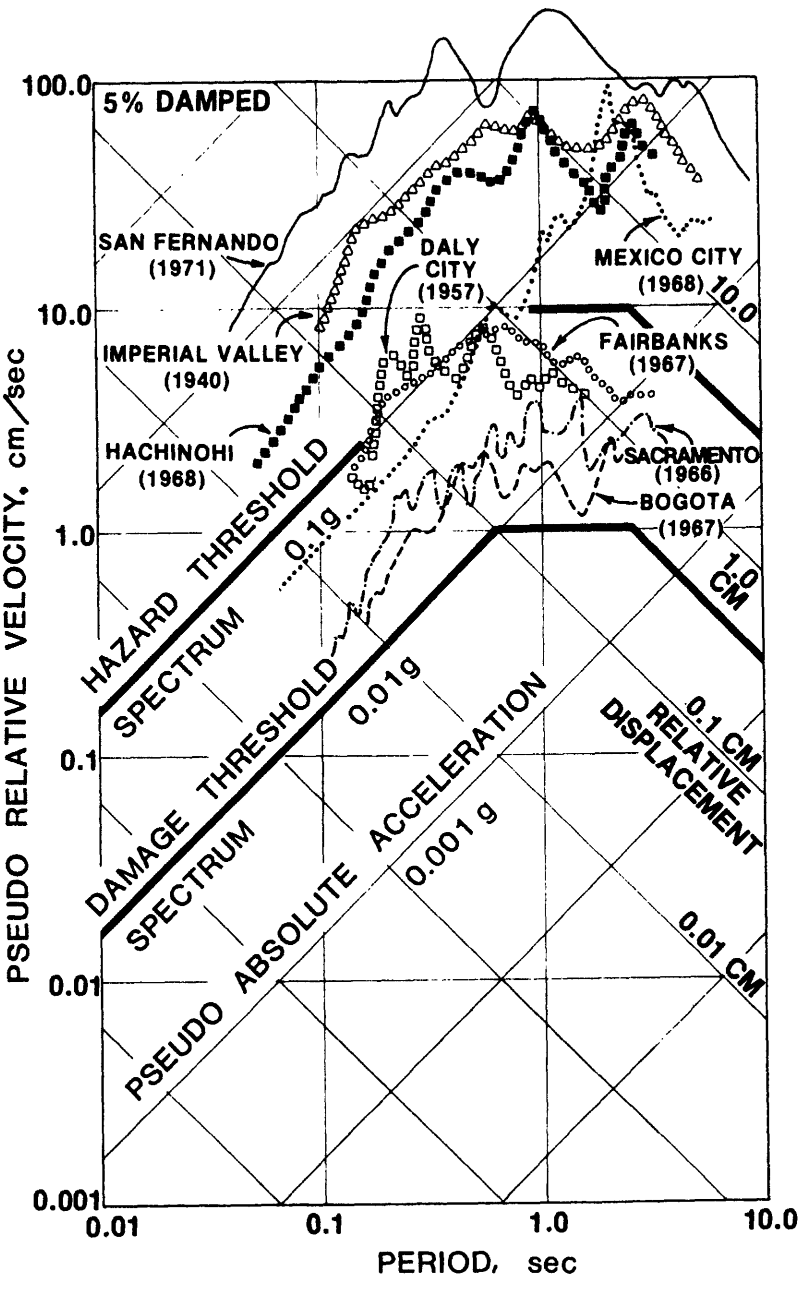


Figure 5.--Graph showing the response spectra of horizontal ground shaking experienced in various cities of the World in past earthquakes. The potential for severe damage and collapse of buildings increases as the peak horizontal ground acceleration increases above 10 percent (0.1g) of the force of gravity, about one-third of the level expected in the Mississippi valley in a 50-year period of time.

fall outward, allowing the floors to cascade one on top of the other crushing the occupants between them. In countries where mud, brick,co and adobe are used extensively as construction materials, collapse is often total even to the point of returning the bricks to dust.

Secondary effects such as landslides, fires, tsunamis (in coastal areas), seiches, and flood waves can be generated in a great earthquake.

Landslides are especially damaging, and in some cases account for the majority of the life loss. The 1970 earthquake in Peru caused more than 70,000 deaths, and 50,000 injuries. Of those killed, 40,000 were swept away by a landslide which fell 12,000 feet down the side of Mt. Huascaran. The landslide roared through Yungay and Rauachirca at 200 miles/hr, leaving only a raw scar where the villages had been.

Regional tectonic deformation, the unique feature of a great earthquake, can cause changes in elevation over an area of tens of thousands of square miles. This effect destroyed ports and harbors in the 1964 Alaska earthquake.

The threat from fire frequently increases due to the loss of firefighting equipment destroyed by earthquake ground shaking and the breaking of the water mains by ground failures. Blocked access highways can hinder the arrival of outside help. The secondary effect of fire is well illustrated by the San Francisco earthquake of 1906, in which only approximately 20 percent of the half billion dollars in damage was estimated to have been due the earthquake, while the remainder was caused by the fire, which burned out of control for several days. One of the greatest disasters of all times, the Kwanto, Japan, earthquake in 1923, also resulted from large fire losses. Almost 40 percent of those killed perished in a firestorm which engulfed an open place where people had gathered in an attempt to escape the conflagration.

Other secondary effects include the disruption of electric power and gas service; both effects contribute to fire damage. Also, highways and rail systems are frequently put out of service, presenting special difficulties for rescue and relief workers.

Water in tanks, ponds, and rivers is frequently thrown from its confines. In lakes, an oscillation known as "seiching" occurs, causing the water to surge from one end to the other, reaching great heights and overflowing the banks. After the 1964 earthquake in Alaska, for example, water rose 6 feet at Memphis, Tennessee, 5,000 miles from the epicenter.

Aftershocks of a great earthquake can last for several decades. They can trigger additional losses and disrupt the populace.

ASSESSMENT OF POTENTIAL RISK IN THE CENTRAL UNITED STATES

The assessment of the potential risk (chance of loss) from earthquake hazards in an urban area is a complex task requiring:

-- An earthquake hazards model.
-- An exposure model (inventory).
-- A vulnerability model.

A schematic illustration of the total range of considerations is shown in Figure 6. Each model is described briefly below with additional detail being provided by either the papers contained in this report or the references.

Earthquake Hazards Model--(See papers by Hays, Nuttli, and Johnston).

Assessment of risk is closely related to the capability to model the earthquake hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, and regional tectonic deformation. Most of the spectacular damage and loss of life in an earthquake is caused by partial or total collapse of buildings as a consequence of the severity and duration of the horizontal ground shaking. However, ground failures triggered by ground shaking (i.e., liquefaction, lateral spreads) can also cause substantial damage and losses. For example, during the 1964 Prince William Sound, Alaska, earthquake, ground failures accounted for about 60% of the estimated $500 million total loss with landslides, lateral spread failures, flow failures, and liquefaction causing damage to highways, railway grades, bridges, docks, ports, warehouses, and single family dwellings. Surface faulting, which is generally confined to a long narrow area, has not

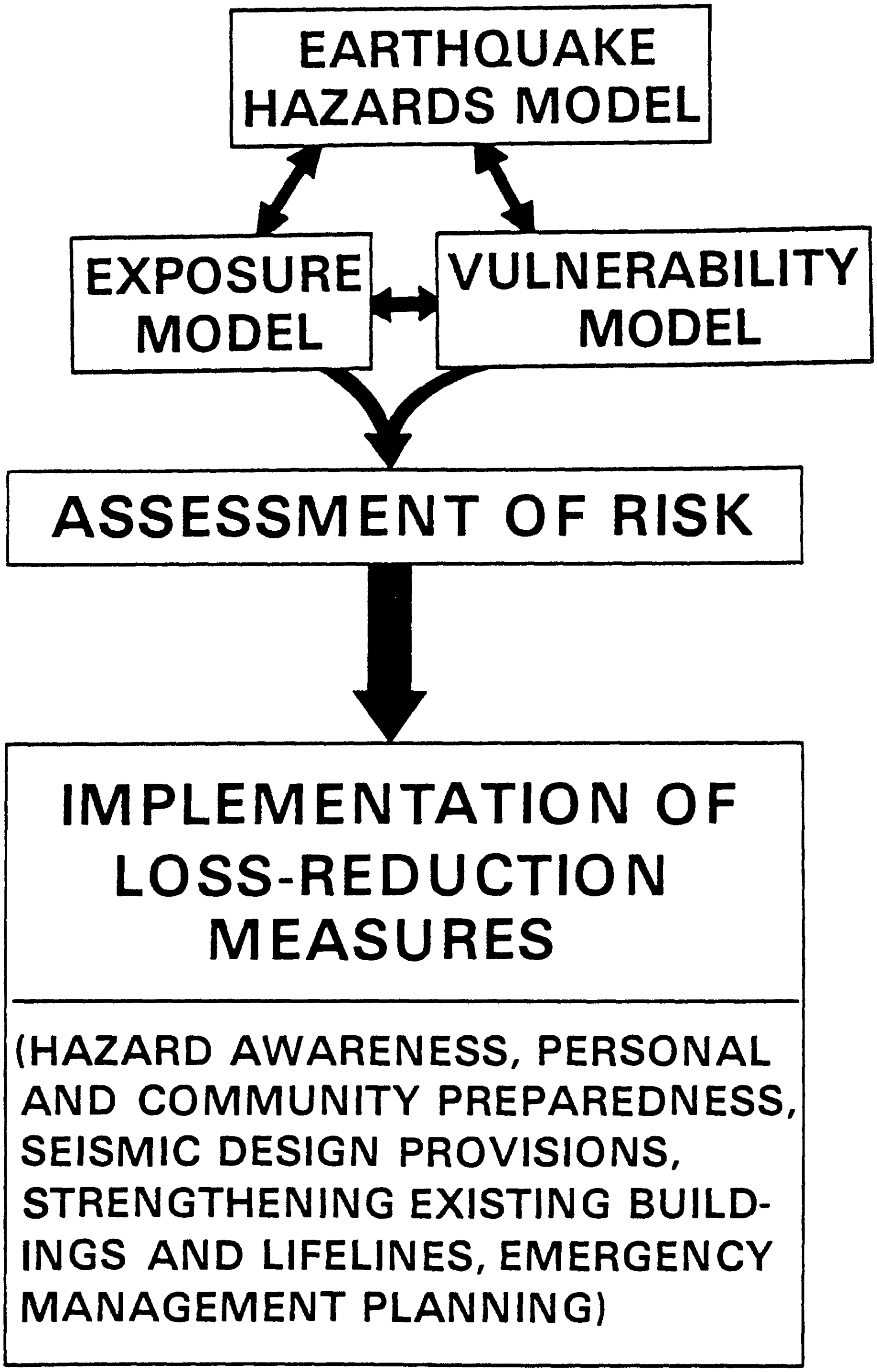


Figure 6. Diagram showing the wide range of evaluations that are part of the overall process of earthquake hazards reduction and risk assessment. The models for earthquake hazards, exposure, and vulnerability are important elements of the overall process that leads to implementation of loss-reduction measures. New information, gained from post earthquake investigations and research, is an important part of the process.

occurred anywhere in the Eastern United States except possibly in the 1811-1812 New Madrid earthquakes. Surface faulting, which generally always occurs in earthquakes of magnitude 5.5 or greater in the Western United States, has damaged lifeline systems and single family dwellings, but has not directly caused deaths and injuries.

The earthquake hazards model must answer the following question explicitly:

1. Where have past earthquake occurred? Where are they occurring now?
2. Why are they occurring?
3. How often do earthquakes of a certain size (magnitude) occur?
4. How bad (severe) have the physical effects (hazards) been in the past? How bad can they be in the future?
5. How do the physical effects (hazards) vary spatially and temporally?

Exposure Model

The spatial distribution of things and people exposed to earthquake hazards is called inventory. The inventory is one of the most difficult models to characterize because it changes with time and existing buildings are altered. For risk assessment, the term structure is used to refer to any object of value that can be damaged by the earthquake hazards of ground shaking, surface faulting, earthquake-induced ground failure, and regional tectonic deformation. Some generalizations involving sampling theory are usually made to facilitate the inventory process. The various categories of structures include:

1. Buildings (residential, agricultural, commercial, institutional, industrial, and special use).

2. Utility and transportation structures (electrical power structures, communications, roads, railroads, bridges, tunnels, air navigational facilities, airfields, and water front structures).

3. Hydraulic structures (earth, rock, or concrete dams, reservoirs, lakes, ponds, surge tanks, elevated and surface storage tanks, distribution systems, and petroleum systems).

4. Earth structures (earth and rock slopes, major existing landslides, snow, ice, or avalanche areas, subsidence areas, and natural or altered sites having scientific, historical, or cultural significance).

5. Special structures (conveyor systems, ventilation systems, stacks, mobile equipment, tower, poles, signs, frames, antennas, tailing piles, gravel plants, agricultural equipment, and furnishings, appendages, and shelf items in the home or office).

Vulnerability Model (See papers by Beavers, Hanson, Cassaro and Chernoff, Naugle, and Weber).

A structure consists of many elements. In principle, to predict losses, the contribution of each individual element to the total response of a structure must be modeled. In practice, certain simplifications and generalizations are made to facilitate the analysis.

Vulnerability is a term describing the susceptibility of a structure or a class of structures to damage. The prediction of the actual damage state that a structure will experience when subjected to a particular earthquake hazard (such as ground shaking) is very difficult, as a consequence of:

-- Irregularities in the quality of the design and construction (e.g., some are designed and built according to earthquake-resistant design provisions of a building code; some are not).

-- Variability in material properties.

-- Uncertainty in the level of ground shaking induced in the structure as a function of magnitude, epicentral distance, and local site geology.

-- Uncertainty in structural response to earthquake ground shaking, especially in the range where failure occurs.

A fragility curve that shows probability of damage versus level of ground motion can be used to represent failure of a specific type of structure (or elements of a structural system) when it is exposed to the dynamic forces of ground shaking. For most structures, damage occurs as a function of the amplitude, frequency composition, and duration of ground shaking and manifests itself in various damage state ranging from "no damage" to "collapse." Specification of the damage states of a structure is very difficult because each damage state is a function of the lateral-force-resisting system of the structure and the severity of the hazard expressed in terms of forces.

OPTIONS FOR PLANNING, RESEARCH, AND MITIGATION (See papers by Gori, Hanson, Johnson, and Jones).

In conjunction with an assessment of the potential risk from earthquake hazards, explicit answers are needed for the following questions:

-- What are the viable options for planning, research, mitigation, response, and recovery to reduce potential losses from earthquake hazards?

-- What research is needed to provide sound technical and societal bases for devising loss-reduction measures.

CENTRAL UNITED STATES EARTHQUAKE PREPAREDNESS PROJECT (CUSEPP) AND CENTRAL UNITED STATES EARTHQUAKE CONSORTIUM (CUSEC)

CUSEPP - CUSEPP was initiated in 1982 by FEMA. The short-term goals were to: 1) to prepare isoseismal maps of selected scenario earthquakes in the New Madrid seismic zone, 2) to develop inventories of structures, lifelines, and critical facilities in selected cities of the Central United States, and 3) to assess the risk in these cities. The six cities selected in the initial pilot phase of the project were Little Rock, Arkansas; Carbondale, Illinois; Evansville, Indiana; Paducah, Kentucky; Popular Bluff, Missouri; and Memphis, Tennessee. They were selected on the basis of these factors:

-- Population.

-- Exposure to potential earthquake ground-shaking hazard defined by the scenario earthquake.

-- Types of architecture and structures, including lifelines.

The long-term goals of CUSEPP are to:

-- Increase the awareness of public officials and the private sector in the Central United States of earthquake hazards and the potential risk.

-- Accelerate the development, adoption, and implementation of strategies to mitigate the hazards and to reduce potential losses.

-- Improve earthquake response plans for dealing with the immediate consequences of a major earthquake.

Two significant reports have been produced by CUSEPP. They are:

-- Estimation of Earthquake Effects Associated with a Great Earthquake in the New Madrid Seismic Zone, U.S. Geological Survey Open-File Report 83-178, 81 p., 1983.

This report gives specific intensity maps for the six cities near the epicentral region of the scenario earthquake, in a composite based on the 1811-1812, New Madrid and the 1895 Charleston, Missouri, earthquakes.

-- As assessment of damage and casualties for six cities in the Central United States Resulting from Earthquakes in the New Madrid Seismic Zone, Federal Emergency Management Agency Report, 195 p., 1985

This report presents the procedures used to make an assessment of potential earthquake losses in the six cities. Losses were based on the composite scenario earthquakes described in the first report and fragility curves.

CUSEC - CUSEC was formed by FEMA in Fiscal Year 1983. CUSEC consists of representatives of the seven Mississippi valley states that are expected to experience ground shaking of at least Modified Mercalli Intensity IX (severe structural damage) in the proposed scenario earthquakes. The goal of CUSEC is to ensure a coordinated program for achieving earthquake preparedness and mitigation goals common to all seven States.

WORKSHOP PROCEDURES

The procedures used in the workshop were designed to enhance the interaction between all participants and, to facilitate achievement of the general and specific objectives of the workshop stated earlier in the report. The following procedures were used:

Procedure 1: A meeting was held in October 1985 in Gatlinburg, Tennessee, in conjunction with a meeting of CUSEC in conjunction with a meeting of CUSEC to plan the workshop.

Procedure 2: Research reports and preliminary technical papers were commissioned and prepared in advance by selected participants. These documents, along with USGS and FEMA reports, were distributed at the workshop for use as basic references and a framework for discussion. The technical reports and papers prepared by selected participants were finalized within 60 days after the workshop and are contained in this publication as a permanent record.

Procedure 3: Scientists, engineers, planners, emergency management specialists, and public officials gave oral presentations in four plenary sessions and three discussion groups. The discussion groups were repeated on the second day so that everyone could have an opportunity to participate in two different groups. The objectives were to: 1) integrate scientific research and hazards awareness and preparedness knowledge, 2) define the scope of the problem indicated by the session theme, 3) clarify what is (and is not) known about earthquake hazards in the Central United States and, 4) identify areas where knowledge is still critically needed. These presentations served as a summary of the state-of-knowledge and gave a multidisciplinary perspective.

Procedure 4: To test the present level of hazard awareness and to determine the perspectives of the participants, a questionnaire was utilized in the first plenary session. It is included below for completeness along with the results.

Questionnaire

Assessment of the Adequacy of the Technical Data in the Mississippi Valley Area

Please circle the number which best represents your judgment about the adequacy of the existing technical data in the Central United States for topics described below. Number 5 represents the highest rating; Number 1 the lowest.

Question: How do you rate the current geologic, seismology, and engineering data bases in terms of their adequacy for:

	Low		Med	High	
a. Research	1	2	3	4	5
b. Development and Implementation of					
-- Hazard maps	1	2	3	4	5
-- Earthquake-resistant design criteria	1	2	3	4	5
-- Land-use decisions	1	2	3	4	5
-- Inspection and review of new and existing buildings	1	2	3	4	5
-- Education and training	1	2	3	4	5
-- Response planning	1	2	3	4	5

Results of Questionnaire

The responses of the participants were as follows:

-- Eighty percent of the participants rated the adequacy of the technical data for use in research as ranging from 3 to 4.

-- Sixty-three percent of the participants rated the adequacy of the technical data for use in preparation of hazard maps as ranging from 3 to 4.

-- Sixty-three percent of the participants rated the adequacy of the technical data for use in developing design criteria as ranging from 3 to 4.

-- Seventy-four percent of the participants rated the adequacy of the technical data for use in formulating land-use decisions as ranging from 2 to 3.

-- Seventy-nine percent of the participants rated the adequacy of the technical data for use in developing a procedure for inspection and review of new and existing buildings as ranging from 2 to 3.

-- Sixty percent of the participants rated the adequacy of the technical data for use in education and training as ranging from 3 to 4.

-- Seventy percent of the participants rated the adequacy for the data for response planning as ranging from 2 to 3.

These responses suggest that some of the participants were not aware of existing maps and reports.

Procedure 5: A certificate was awarded to each participant at the end of the workshop.

PLENARY SESSIONS

Following introductory remarks by Lacy Suiter, Tennessee Earthquake Management Agency, the workshop process was developed in four plenary sessions moderated alternately by Walter Hays (USGS) and Gary Johnson (FEMA). The themes, objectives, and speakers for each plenary session are described below.

Session 1: Current knowledge of earthquake hazards in the Central United States

Objective: Using a briefing format, the speakers provided fundamental information on: 1) the "ideal" and the actual earth sciences data bases that are driving current research and mitigation programs and activities in the Central United States, and 2) the current and projected state-of-knowledge of the earthquake hazards of ground shaking, ground failure (liquefaction and landslides) and tectonic deformation in the Central United States. The best explicit answers were provided on the basis of existing data and knowledge to the questions:

-- Where have past earthquakes in the Central United States occurred?
-- Where are earthquakes occurring now?

-- Why do earthquakes occur in the Central United States?

-- How often do earthquakes having magnitudes 6 or greater recur in the Central United States?

-- How severe have the physical effects of ground shaking, ground failure, and tectonic deformation been in past earthquakes?

-- What could happen if a major earthquake occurred tomorrow in the Central United States?

Speakers: Ideal and Actual Data Bases
--Walter Hays, U.S. Geological Survey

The Current and Projected State-of-Knowledge on Earthquake Hazards
--Otto Nuttli, St. Louis University

Session II: Applications of Current Knowledge on Earthquake Hazards

Objective: Panelists, using a briefing format, provided fundamental information on the types of applications that are now being made and others that can be made on the basis of the existing technical data base and state-of-knowledge on earthquake hazards in the Central United States. Examples of the types of data needed to construct maps and to foster mitigation applications at different scales (national, regional, urban, community, and engineering) were cited to provide a framework of discussion for discussion groups. Technical issues that lead to controversy and hinder applications were identified.

Panelists: Availability and Applications of Earth Sciences Data at National, Regional, and Community Scales
--Arch Johnston, Tennessee Earthquake Information Center

Applications of Earth Sciences Data in Community Preparedness Planning
--Paula Gori, U.S. Geological Survey

Engineering Applications of Earth Sciences Data (Codes, Seismic Microzoning, Engineered Construction)
--James Beavers, Martin Marietta Energy Systems, Inc.

Session III: Overview of Earthquake Hazards Reduction Efforts in the Central United States

Objective: To acquaint all participants with the objectives of the Central United States Earthquake Preparedness Project (CUSEPP) and its work elements and to define what needs to be done to achieve total implementation of CUSEPP.

Speakers:
--Gary Johnson, Federal Emergency Management Agency
--Erie Jones, Central U.S. Earthquake Consortium (CUSEC)
--Wilbur Buntin, Kentucky Division of Disaster and Emergency Services

Session IV: New Information

Objective: To review new technical data gained from the January 31, 1986, Ohio and September 19, 1985, Mexico earthquakes and to relate these data and experiences to the Central United States.

Speakers:
--Walter Hays, U.S. Geological Survey
--Otto Nuttli, St. Louis University

DISCUSSION GROUPS: Three discussion groups were formed twice, once each day, to discuss topics of concern in the Central United States. Thus, the themes and objectives of each group were presented to approximately two-thirds of the participants.

Group 1: Technical Information Needed for Development and Adoption of Earthquake Hazards Mitigation Measures

Objective: To focus on the types of detailed information that are needed for the development and adoption of land use and building practices and codes on a State, country, or city basis. The following questions were addressed:

-- Are detailed soils data required?
-- Are maps of acceleration required?

-- What are appropriate site selection criteria?
-- What are the most important nonstructural considerations?
-- What are the political and economic considerations as they relate to acquisition of reliable technical data?
-- What makes the process of adoption of loss-reduction measures and their implementation happen?
-- How do technical data bases feed that process?

Moderator: Robert Hanson, University of Michigan

Panelists:
-- Mike Cassaro, University of Louisville
-- Warner Howe, Gardner & Howe
-- Martin Walsh, St. Louis Building Department

Group II: Public Sector Information Needs for Responding to Earthquakes

Objective: To focus on the degree of detail needed to develop response plans for life protection. The following key questions were answered:

-- What information is needed for planning for the immediate post-event period and the intermediate recovery period?
-- Is seismic microzonation needed in vulnerability assessments developed for response planning?
-- What data currently exist to allow for acceleration of the process of delineation of hazards on an urban scale?
-- How can these data be utilized?
-- What types of systems must exist to implement the response plans?
-- What technical information will be needed during the immediate and the intermediate response and recovery periods?

Moderator: Charles D. Jones, Illinois Emergency Services and Disaster Agency

Panelists:
--Neil Weber, Murray State University
--Tom Durham, Tennessee Emergency Management Agency
--John Keefer, Kentucky Geological Survey
--Jerry Vineyard, Missouri Department of Natural Resources

Group III: Private Sector Information Needs and Incentives for Earthquake Response Planning and Mitigation

Objective: To identify the types of information required to provide incentives for the private sector to initiate response planning and mitigation activities. Participants addressed questions such as:

-- Is existing earthquake hazards information sufficiently credible to engender belief in it and to trigger the desire to take action?
-- If not, what else is needed?
-- What types of presentations of loss potential are needed?
-- What specific information is needed for hazards identification and mitigation techniques by the private sector?
-- What roles do the insurance industry play in ensuring private sector awareness and concern and what are the insurance industry needs?
-- If more detailed geologic data are needed, is it needed now, before any mitigation actions can be taken?
-- What role does the State play in bringing together the scientific researchers and the industrial sector?

Moderator: James Beavers, Martin Marietta Energy Systems, Inc.

Panelists: --James M. Everett, Fulton County Kentucky
--John D. Hoyle, St. Luke Hospital, Inc.

REPORT OF THE DISCUSSION GROUPS

Group I: Technical Information Needs of Mitigation Measures in the Central United States

The participants in the two sessions of this working group began with two premises:

-- Earthquake hazards can be mitigated by improving capabilities of man-made structures to withstand strong ground shaking and/or soil failures.

-- When increasing the seismic safety of structures the first concern is to ensure the safety of people from death and serious injury; the second is continuation of the primary function of the structure after the earthquake.

Information Needs: The technical information needed for increasing the seismic safety of structures is generally available now; however, it is scattered in many different reports, maps, and documents. The NEHRP provisions for earthquake-resistant design pulls the basic information together and represents an adequate basis for the enactment of building codes in the Central United States, or for the voluntary adoption of seismic safety measures in building construction. Additional technical information is needed to quantify phenomena such as: 1) long distance transmission of seismic waves in the Central United States, 2) soil amplification of ground motion, and 3) soil-structure interaction. The September 19, 1985, Mexico earthquake pointed out the need for more research and data on these phenomena.

Short term recommendations (1-2 years): The participants recommended efforts to:

1) Increase the awareness of earthquake hazards of policymakers and elected officials.

2) Provide continuing education for code officials, architects, planners, engineers, constructors and inspectors on seismic loads and building response.

3) Stimulate popular support for the implementation of mitigation measures by the construction industry.

Strategies suggested for implementing these recommendations during the next 1-2 years included:

-- Rewriting in nontechnical language the essential elements of the NEHRP provisions, condensing them to a few pages.

-- Establishing the cost/benefit ratio for seismic safety construction in the Central United States.

-- Providing information to the primary "target audience" of elected State and local officials and the secondary "target audience" of appointed officials. The first group have the ultimate say in mitigation measures relative to construction.

-- Planning a demonstration project for 1 to 2 story structures (for example, school buildings) to educate elected and appointed officials, building 5nspectors, and others on criteria, methods, and costs.

-- Utilizing the academic sector to train professionals on the principles of seismic safety in buildings.

-- Involving the financial sector (insurance, banking, etc.) in an effort to stimulate implementation of mitigation measures by the building industry.

-- Continuing ongoing efforts in public awareness to expand popular support for enactment of mitigation measures.

Long-Term Recommendations (3-5 years): The participants recommended efforts to:

1) Produce new information and improve hazards maps for the Central United States, focusing on ground shaking and soil failures and their effects.

2) Collect and synthesize information on the behavior of various classes of buildings under strong ground shaking.

3) Adopt and enforce the earthquake provisions of a modern building code and implement them in construction practice.

Strategies suggested for implementing these long-term recommendations included:

-- Incorporating new knowledge on long distance seismic wave transmission and the potential for soil-structure interaction into building codes.

-- Deploying strong motion instruments at selected sites, such as in buildings of a specified height and at surface and subsurface locations.

-- Using a panel of local experts to identify special study areas--zones which have a high probability of soil failure and the development of new buildings.

-- Raising the legal liability issue, especially to owners.

-- Producing data to explain fault activity in the Central United States outside of the New Madrid seismic zone.

-- Establishing the feasibility of retrofitting existing buildings in terms of assuring life safety (Note: it may be possible to achieve the goal of life safety without a major retrofit program.)

-- Performing research on energy absorption and base isolation techniques that could be applied in the Central United States.

-- Demonstrating the cost effectiveness of earthquake-resistant design of a potentially vulnerable segment of the building stock (for example, schools).

Group II: Public Sector Information Needs for Responding to Earthquake

The participants of this working group identified the following needs:

1) Development of a computerized data management system. The large quantity of diverse technical data that now exists for the Central United States makes the development of a computerized data management system a top priority task. Many types of information should be contained in a data base, including: critical facilities, (dams, hospitals, nuclear power plants, emergency response command centers, etc.), lifelines (highways, bridges, utilities, airports), seismic network data (seismicity and strong ground motion), soil data (stiff, intermediate, and soft soils, soil susceptible to liquefaction), slope characteristics (steepness, water table, susceptibility to landslides), etc.

2) Vulnerability information on critical facilities. Damage to critical facilities in a major earthquake will have far-reaching impact, therefore, there is a great need to refine our knowledge of their potential vulnerability.

3) Data to perform a seismic microzoning study. Seismic microzoning is a part of the process of evaluating earthquake hazards in a region that leads to the definition of zones expected to experience the same severity of a hazard. Seismic microzoning provides the potential user of an area with the design criteria needed to make the best possible use of the area. Although the concept of seismic microzoning is fairly advanced in Europe and Japan, the methodology is still being refined in the United States. Also, no standard methodology exists for seismic microzonation.

Short and Long-term Recommendations:

The participants recommended that:

1) CUSEC serve as coordinator for computerization of relevant multidisciplinary data needed for earthquake hazards evaluation, seismic microzoning, and response planning.

2) A procedure be established through CUSEC to identify the critical facilities in the Central United States and to prioritize detailed studies to assess their potential vulnerability.

3) Consideration be given to a pilot seismic microzoning study.

Strategies suggested for implementing these recommendations included:

-- Taking advantage of experience on computerized data systems gained by Southern California Earthquake Preparedness Project in Southern California.

-- Working with local communities to collect information on critical facilities.

-- Incorporation of the "lessons" learned from the 1985 Mexico earthquake in terms of critical facilities and search and rescue procedures.

-- Establishing a study group to evaluate the feasibility of a pilot seismic microzonation study. (Note: A preliminary seismic microzonation study of Memphis was conducted in 1980 by Sharman and Kovacs under the auspices of USGS. The report of this study should be carefully reviewed).

-- Microzonation, when pursued, should be linked with prioritized critical facilities and incorporate both urban and rural perspectives.

-- Continue and improve the dialogue between scientists and emergency managers.

Group III: Private Sector Information Needs and Incentives for Earthquake Response Planning

The participants of Group III agreed that adequate technical data and information on earthquake hazards exist, but they must be collected, synthesized, translated, and packaged in formats that will meet industry needs better than at the present time.

Short and Long-Term Recommendations:

The participants recommended that:

1) Earthquake education action programs be developed for the management of specific private sector industries such as medical care/hospitals, communications, and manufacturing.

2) Efforts be undertaken through professional and educational societies and State licensing boards, etc., to require inclusion of relevant material on earthquake hazards in the curriculum for engineers, architects, and others.

3) The insurance industry become a partner with the public sector in fostering earthquake hazards reduction measures nationwide.

4) Efforts be increased to adopt and enforce the earthquake-resistant design provision of a modern building code and that the nonstructural code and regulations be put in place.

5) Public officials provide industry with adequate means of self-protection through building codes, tax incentives, insurance, etc. (Note: the price for requesting industry support in earthquake hazards reductions should be a personal commitment of public officials to the same goals).

Strategies suggested for implementing these recommendations included:

-- Prepare seminars, technical information packages, information or incentives, and brochures, etc. to educate industry management.

-- Incorporate information on earthquake hazards in a more uniform way in the curriculum of academic institutions and into the professional licensing process.

-- Find one or more "champions" in the insurance industry to play a major role in earthquake hazards reduction and implementation of mitigation measures.

-- Adopt legislation that will stimulate the positive response of the private sector/industry.

-- Determine the "bottom line" for earthquake risk and communicate it to appropriate industry leaders.

APPENDICES

Three appendices are included with this report. They are:

Appendix A: Glossary of technical terms used in the evaluation of earthquake hazards and risk.

Appendix B: Participants in the workshop

Appendix C: Location of strong motion instruments in the Central United States

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EVALUATION OF THE WORKSHOP ON "EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE HAZARDS REDUCTION IN THE CENTRAL UNITED STATES"

by

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This two-day workshop was attended by nearly 90 individuals representing local, regional, state and federal governments, emergency and planning agencies, researchers, the private sector, and public interest groups. The meeting offered information in plenary sessions designed to provide participants wtih current knowledge about the earthquake hazard in the Central U.S., how that knowledge is presently being applied at federal, regional and community levels, and an overview of present and needed earthquake hazard reduction efforts in this region.

Discussion groups met to identify three areas of information needs: technological information needed to develop and implement earthquake mitigation measures, public sector information needs to improve response, and private sector information needs to improve planning and mitigation.

At the conclusion of the workshop participants were asked to evaluate the information that was presented, the structure of the workshop itself, and to rate the impact attendance had on their own levels of awareness and concern. Responses were elicited on a five-point scale: 1 and 2 representing the lowest level of agreement, 3 moderate agreement, and 4 and 5 highest agreement or a "yes" response (see question #5, Figure 1). Evaluations were completed by 30 participants, but as all respondents did not answer all questions, totals do not necessarily add to 30 or 100% (see Figure 2).

Evaluations indicate that the workshop was successful in reaching its goals. Nearly 80% of respondents found the workshop very successfully defined the current knowledge of seismic hazards in the Central U.S. Eighty percent

Figure 1

Evaluation by Individual Participants

EVALUATION FORM
EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE
HAZARDS REDUCTION IN THE CENTRAL UNITED STATES

Please circle the number which best represents your response to the following questions: Number 5 represents the highest rating and number 1, the lowest. Your answers will help us evaluate the workshop.

	Low 1&2	Med 3	High 4&5
1. Did you find the workshop to be useful for defining:			
a. Current knowledge of earthquake hazards in the Central United States?..........	2	4	23
b. Application of current knowledge on earthquake hazards?.....	6	15	9
c. Earthquake hazards reduction efforts in the Central United States?..........	4	13	12
2. Did you find the workshop to be useful for assessing technical information needed for:			
a. Development and adoption of earthquake hazards mitigation measures?..........	6	11	12
b. Public sector response to earthquakes?..........	6	13	9
c. Private sector information on earthquake response planning and mitigation?..........	11	12	7
3. Did the workshop benefit you or your organization by:			
a. Providing new sources of information and expertise you might want to utilize in the future?..........	3	2	25
b. Establishing better understanding of the problems faced by researchers and decisionmakers?..........	2	6	20
4. Did you find the following activities useful:			
a. Formal presentations?..........	2	6	20
b. Discussions following the formal presentations..........	4	9	17
c. Discussion group sessions..........	3	7	20
d Notebook abstracts..........	1	8	20
e. Information discussions during breaks and after hours?......	6	6	18
5. If the clock were turned back and the decision to attend the workshop were given to you again, would you want to attend?	2	-	28
6. Should future workshops be planned to continue the work initiated at this meeting?..........	--	--	29
7. Prior to attending this workshop, I would rate my <u>awareness</u> of the earthquake threat in the Central United States as..........	3	4	23
8. Prior to attending this workshop, I would rate my <u>concern</u> about the state-of-earthquake preparedness in the Central United States?..........	3	5	21
9. I now rate my awareness as..........	1	1	28
10. I now rate my concern as..........	--	4	26

Figure 2

Evaluation by Percentages of Participants

EVALUATION FORM

EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE HAZARDS REDUCTION IN THE CENTRAL UNITED STATES

Please circle the number which best represents your response to the following questions: Number 5 represents the highest rating and number 1, the lowest. Your answers will help us evaluate the workshop.

	Low 1&2	Med 3	High 4&5
1. Did you find the workshop to be useful for defining:			
a. Current knowledge of earthquake hazards in the Central United States?........	7	13	77
b. Application of current knowledge on earthquake hazards?.....	20	50	30
c. Earthquake hazards reduction efforts in the Central United States?........	13	43	40
2. Did you find the workshop to be useful for assessing technical information needed for:			
a. Development and adoption of earthquake hazards mitigation measures?........	20	37	40
b. Public sector response to earthquakes?........	20	43	30
c. Private sector information on earthquake response planning and mitigation?........	37	40	23
3. Did the workshop benefit you or your organization by:			
a. Providing new sources of information and expertise you might want to utilize in the future?........	10	7	83
b. Establishing better understanding of the problems faced by researchers and decisionmakers?........	7	20	67
4. Did you find the following activities useful:			
a. Formal presentations?........	7	20	67
b. Discussions following the formal presentations........	13	30	57
c. Discussion group sessions........	10	23	67
d Notebook abstracts........	3	27	67
e. Information discussions during breaks and after hours?......	20	20	60
5. If the clock were turned back and the decision to attend the workshop were given to you again, would you want to attend?	7	--	93
6. Should future workshops be planned to continue the work initiated at this meeting?........	--	--	97
7. Prior to attending this workshop, I would rate my <u>awareness</u> of the earthquake threat in the Central United States as........	10	13	77
8. Prior to attending this workshop, I would rate my <u>concern</u> about the state-of-earthquake preparedness in the Central United States?........	10	17	70
9. I now rate my awareness as........	3	3	93
10. I now rate my concern as........	--	13	87

Percentages based on total number of evaluations (30). Not all categories = 100 as not all questions were answered by all participants.

thought the workshop portrayed the application of current knowledge from moderately to very well and were similarly satisfied with information about the earthquake hazard reduction efforts (see Figure 2).

Another goal of the workshop was to assess the adequacy of information in several areas. Twenty-three respondents, representing 77% of the group, said the workshop was successful in identifying information needed to develop and adopt earthquake hazard mitigation measures. Seventy-three percent found the presentations useful in identifying information needs in the public sector. But the workshop was somewhat less successful in identifying those information needs in the private sector. Here 11 respondents (37%) rated the workshop effectiveness low and only 23% were very satisfied (see Figures 1 and 2).

Those in attendance were asked to consider whether their participation was beneficial, not only to themselves, but to the organizations they represent. Here 83% rated the workshop very high with a total of 90% satisfied that the meeting had provided them with new sources of information and knowledge of experts upon whom to call in the future. Two-thirds of respondents felt participation gave them a much better understanding of problems faced by researchers and decision makers. Only two participants failed to see that their attendance provided this greater level of understanding (see Figure 1).

The questionnaire then elicited opinions about a number of workshop activities, from formal presentations to large and small group discussions, to materials provided in the workshop notebook and informal information exchanges. Participants found each of these to be useful. In fact, only two respondents rated formal presentations low (see Figure 1). Nearly 90% of the participants ranked the discussions following formal presentations from moderately to very useful and 90% were similarly satisfied with the small group discussions. Notebook abstracts were found to be useful by nearly all participants, only one person found them to be not particularly helpful (see Figure 1). Information discussions during breaks and after hours were found useful by most participants, 60% of whom were very pleased with this aspect of the conference. A few (20%) felt that greater opportunities could have been provided for these informal exchanges.

Given the opportunity to attend a similar workshop in the future, nearly all (93%) of the participants would do so enthusiastically. Support was unanimous for holding future workshops which would continue work initiated at this meeting.

Among the primary goals of this series of workshops are heightening the levels of awareness and concern within the non-scientific community. Responses to questions concerning pre- and post-attendance levels of awareness indicate that participation had a positive effect. Prior to attending the workshop 10% indicated low levels of awareness, 13% moderate awareness, and 77% high awareness. After the conference, only one person felt his awareness remained low, one remained moderate, while 93% rated their awareness levels as high (see Figures 1 and 2).

Levels of concern for pre- and post-participation displayed similar gains. Only 70% indicated high levels of concern prior to attendance. This figure climbed to 87% following the workshop. And where 10% had noted low levels of concern before the workshop, no one left the meeting unconcerned.

Looking at individual questionnaire responses, there were a few individuals that registered no change in levels of awareness and concern. However, these individuals already were highly aware and concerned about seismic hazard potential prior to the workshop.

In summary, evaluations indicate that the workshop was successful in defining the status of the seismic hazard potential in the Central United States and enthusiastic responses indicate, furthermore, that the workshop provided useful insights about available information and programs as well as the scientists and decision makers upon whom to call for assistance in the development and implementation of future hazard reduction programs.

Strong support for the continuation of these efforts has been indicated by those who took part in this evaluation.

EXAMINATION OF THE BODY OF TECHNICAL DATA AVAILABLE FOR ASSESSING THE NATURE AND EXTENT OF EARTHQUAKE HAZARDS IN THE MISSISSIPPI VALLEY AREA AND DEVISING OPTIONS FOR MITIGATING THEIR EFFECTS

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ABSTRACT

An assessment of the earthquake hazards of ground shaking, surface fault rupture, ground failure, and tectonic deformation requires careful integration, analysis, and extrapolation of the available geological, seismological, and engineering seismology data bases. These data bases always have some type of limitation such as lack of data on a particular scale. However, they are adequate on the whole as a basis for creative research and for the development and implementation of loss-reduction measures. Potential applications include: 1) hazards maps, 2) design criteria, 3) landuse, vulnerability, and loss studies, 4) inspection and review, 5) public policy, education, and training, 6) response planning, and 7) postearthquake investigations and transfer of technology.

CHARACTERISTICS OF EARTHQUAKES AND OTHER NATURAL HAZARDS

Earthquakes are one of the twelve natural hazards affecting all parts of the Nation to some degree. The other natural hazards are: avalanches, coastal erosion, drought, floods, hurricanes, landslides, storm surges, tornados, unstable soil, windstorms, and winter storms. When comparing earthquakes with other natural hazards in an area, it is useful to compare the following characteristics: 1) frequency (how often an event of a given size occurs), 2) duration (the length of time the event lasts, 3) area affected (limited area, such as the path of a tornado, or a broad area, such as with most droughts), 4) impact time (the time between the first precursors of the event and its peak impact), and 5) pattern of occurrence (random time occurrence and difficult to predict, as with earthquakes, or predicability seasonal, as with hurricanes, or having some other spatial and temporal pattern).

A detailed comparison of earthquakes with other natural hazards in the Mississippi Valley area is beyond the scope of this paper. However, the characteristics of earthquakes in the Mississippi Valley area will be described below to provide insight for individuals who are concerned with the overall problem of mitigating the effects of earthquake hazards. A major earthquake in the Mississippi Valley has the potential for causing great sudden loss both directly through the primary hazards of ground shaking, surface fault rupture, earthquake-induced ground failure, and tectonic deformation (Figure 1) and the secondary hazards of fire and flooding. Great earthquakes in the Mississippi Valley area occur relatively infrequently (about once every 500-700 years). They have a short duration (zero to a few minutes). They cause: 1) severe structural damage in an area of several thousand square miles (IX-XII on the Modified Mercalli intensity scale), 2) structural damage over an area of several tens of thousands of square miles (VII-IX on the Modified Mercalli intensity scale), and 3) architectural damage (such as damaged chimneys, falling plaster and light fixtures in ceilings, overturned water heaters and bookcases, and other kinds of damage to contents over an area of several hundred thousand square miles (VI-VII on the Modified Mercalli intensity scale). Within this large area of impact (see Figure 2) considerable loss of life, injuries, and social impacts happen as a direct function of the overall state-of-preparedness in the region and the degree to which loss-reduction measures have been implemented.

Prediction of earthquakes is considered to be viable scientifically; however, the capability to provide reliable short-term warnings of imminent earthquakes has not yet been achieved in either California (where most of the research has been conducted) or the Mississippi Valley. Therefore, the impact time of earthquakes in the Mississippi Valley is very short under the best circumstances and no real warning is possible. Although earthquakes tend to recur where they have occurred in the past and long-term forecasts of the size and place of the potential earthquake are clearly feasible, the pattern of occurrence of earthquakes in the Mississippi Valley must be treated now as more or less random within the New Madrid seismic zone (Figure 3).

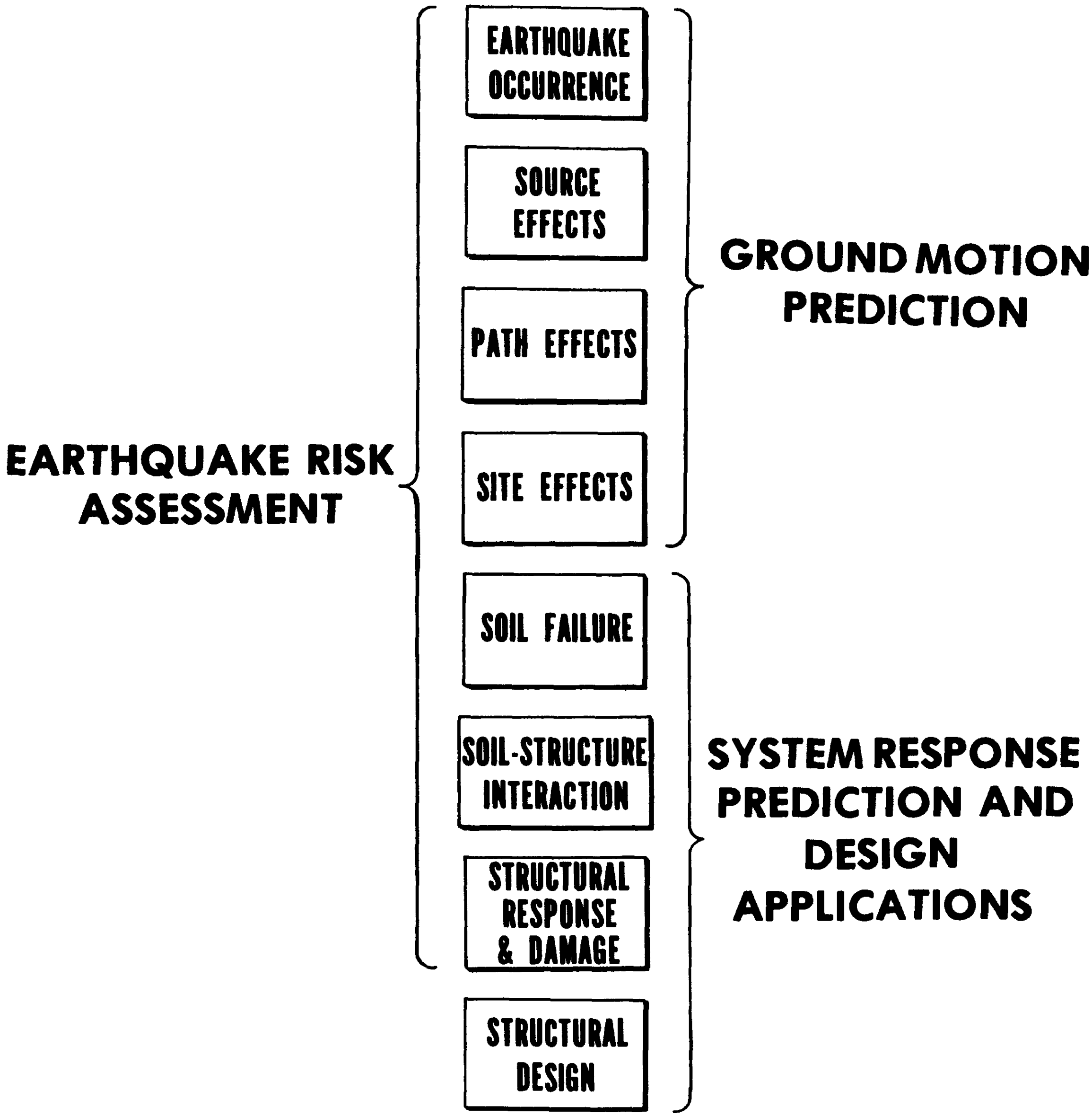

Figure 1.--Schematic illustration of the technical considerations involved in: a) the evaluation of earthquake hazards, b) the assessment of risk, and c) earthquake-resistant design. In the Mississippi Valley area, technical knowledge and data are available to perform all three types of evaluations and to foster implementation, in at least a preliminary way, effective measures to reduce potential life loss and injuries from ground shaking and soil failure in future earthquakes.

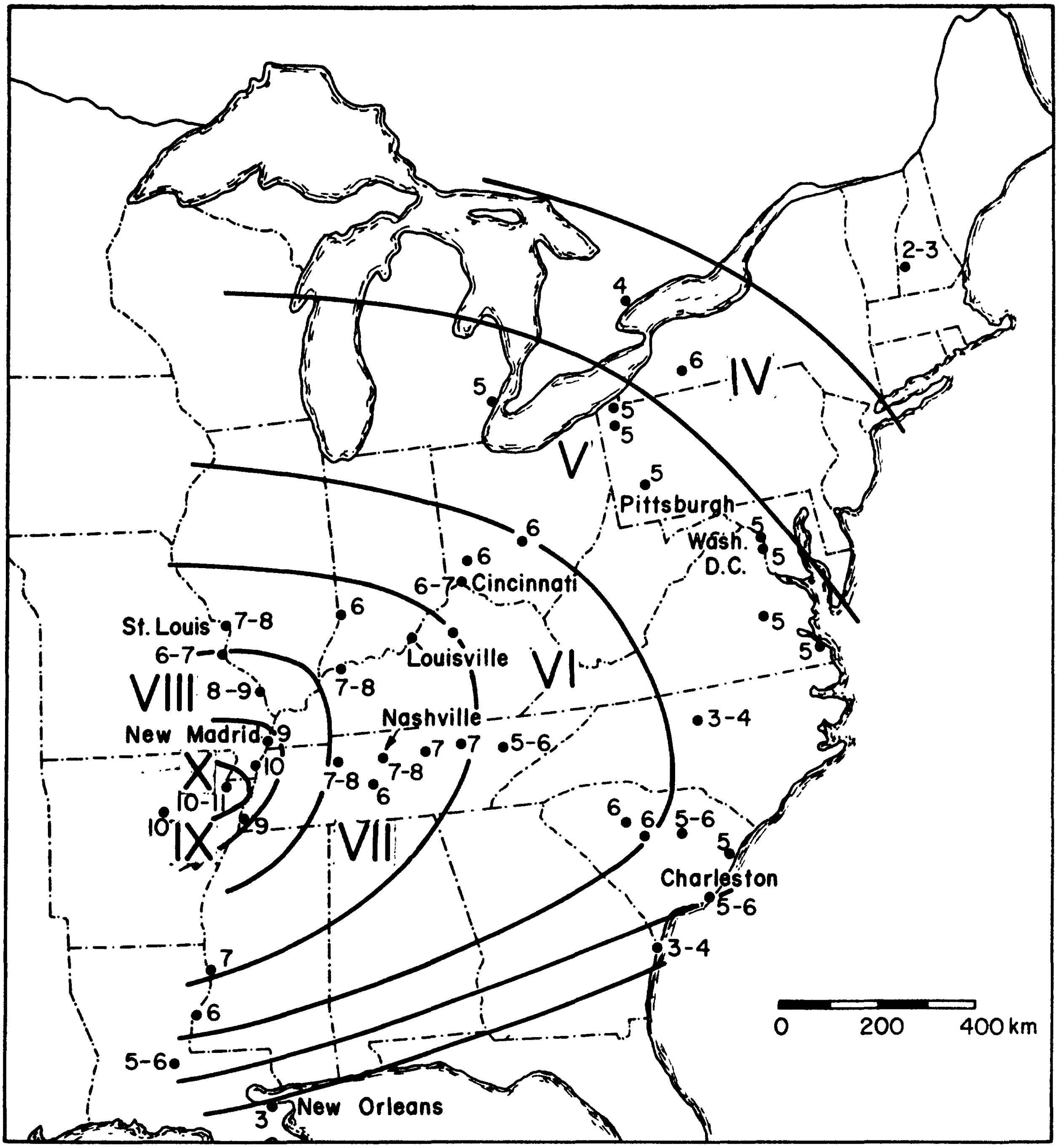

Figure 2.--Isoseismal map of the 1811-1812 New Madrid earthquakes (from Nuttli, 1973).

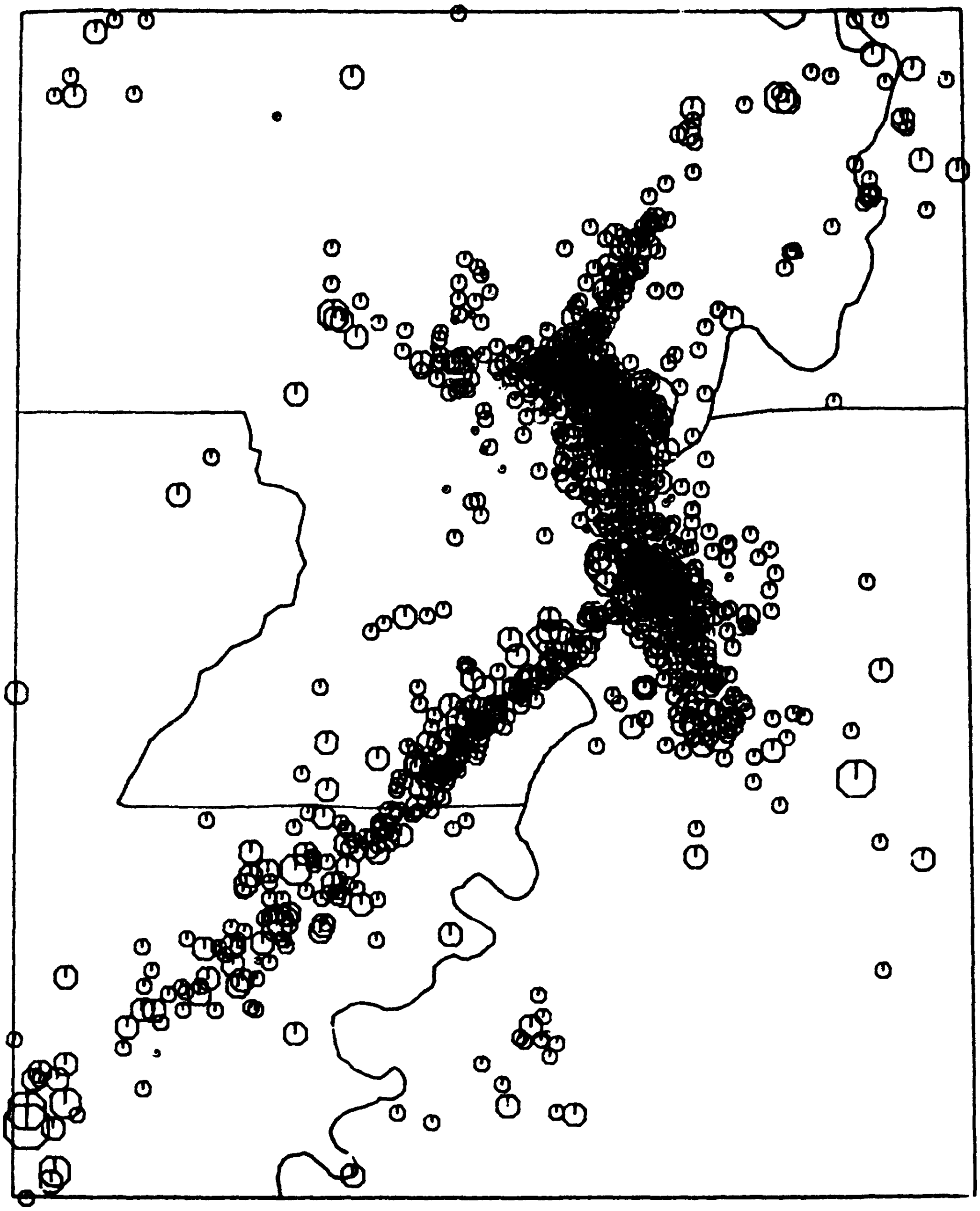

Figure 3.--Map of the New Madrid seismic zone, a buried zone of rifting about 70 km wide and more than 200 km long having 2-3 km of structural relief. The seismic zone was defined by gravity, magnetic, and seismicity data.

At the present time, no region of the country, including the Mississippi Valley, is effectively implementing loss-reduction measures to mitigate the potential effects of a major earthquake nor is any region completely prepared to respond to such an earthquake. Although floods are the most frequent natural hazard and cause annual losses of $3-5 billion, a major earthquake in California or the Mississippi Valley could cause losses of $50 billion or more as well as thousands of deaths and injuries depending upon the time of day and the season of the year when the earthquake occurred.

COMPARISON OF EARTHQUAKE HAZARDS IN THE MISSISSIPPI VALLEY AREA AND THE WESTERN UNITED STATES

When comparing earthquake hazards in the Mississippi Valley and Western United States, scientists/engineers and decisionmakers must be aware of important differences in the hazards of ground shaking, surface faulting, earthquake-induced ground failure, and tectonic deformation. Eight generalized differences are inferred from actual data and judgment and are summarized below:

1) Ground shaking--In terms of peak ground acceleration, earthquake ground shaking in the Mississippi Valley for a given exposure time such as 50 years (the useful life of an ordinary building) is about 40% of the level expected in California (Figure 4). In the Mississippi Valley area, the level of ground motion is not only high, but ground motion also tends to attenuate slowly away from the epicenter and to be characterized by low frequencies and a long duration of shaking. These characteristics of the ground shaking hazard increase the potential for damage to tall buildings (10 stories or more) located as much as 500 miles away from the epicentral area. Normally, significant damage from ground shaking is unexpected at these distances. The potential for damage is greater if the near surface soil/rock column causes amplification of the ground shaking in low frequency bands coinciding with the natural frequency of the tall buildings (as in the 1985 Mexico earthquake).

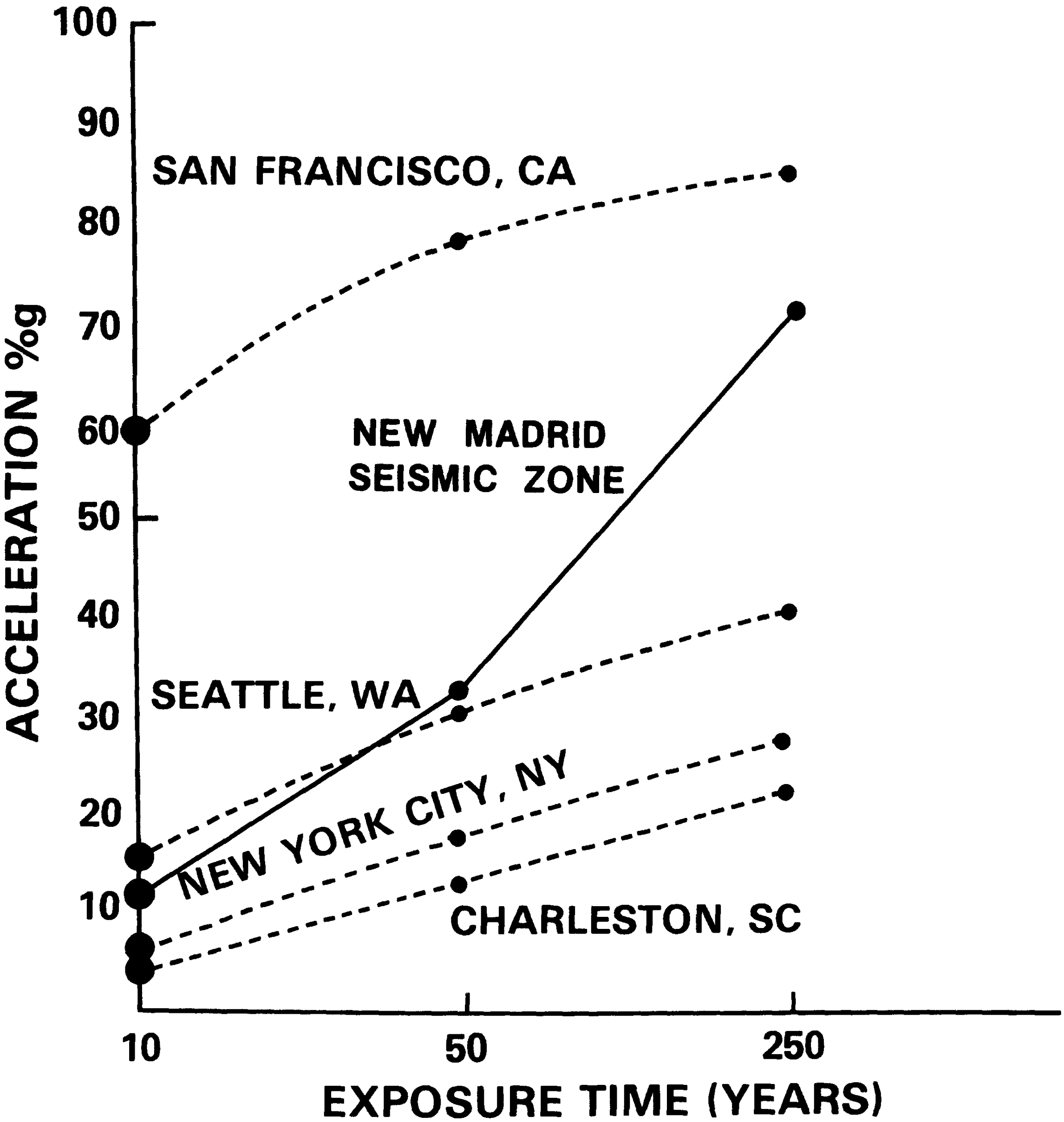

Figure 4.--Comparison of the earthquake ground shaking hazard in the New Madrid seismic zone with other parts of the United States (from Algermissen and others, 1982). The ground shaking is given in terms of peak horizontal bedrock acceleration, exposure time, and a 90 percent probability of nonexceedance. A 50-year exposure time correlates with a 50 year useful life for ordinary buildings.

2) Surface fault rupture--Except for the 1811-1812 New Madrid, Missouri, earthquakes, no historic earthquakes have caused surface faulting in the Mississippi Valley area. Extensive historic surface faulting has taken place in the west on faults that exhibit geologically young displacements (i.e., displacements within the Holocene--last 10,000 year, or the Quaternary--last 2 million years).

3) Recurrence interval--The recurrence interval for great earthquakes in the New Madrid seismic zone is on the order of about once very 500-700 years; whereas, it is about once every 150 years in California.

4) Seismic wave attenuation--The rate of attenuation of seismic energy in the Mississippi Valley area is much slower than in the West, causing a much larger area in the Mississippi Valley to experience disruption of contents and architectural and structural damage in an earthquake. The ratio of the impacted area is roughly 20 to 1.

5) Liquefaction and landslides--The larger area of strong ground shaking in the Mississippi Valley area causes potential liquefaction and landslide. Liquefaction which can occur at intensities on the Modified Mercalli Intensity scale ranging from VI-X is likely to be triggered over a broad geographic area at sites having young, low-density, loosely compacted, water saturated sand deposits.

6) Site amplification--Soil and rock columns in the Mississippi Valley appear to have physical characteristics that can cause amplification of ground motion in selected frequency bands. Sites underlain by thin stiff soils would amplify high-frequency ground shaking; whereas, sites underlain by thick soft soils amplify low-frequency ground shaking. Low-rise buildings are more susceptible to high-frequency ground shaking; whereas, tall buildings are more susceptible to low-frequency ground shaking. Amplification by soil deposits can increase the Modified Mercalli intensity rating (relative to rock) by two intensity units (i.e., from V to VII). Damage can occur in the upper stories of tall buildings if the resonant frequency of the ground

coincides with the resonant frequency of the building and the building is not constructed to withstand these forces.

7) Tectonic deformation--Tectonic deformation, the characteristic feature of earthquakes having magnitudes of 8 or greater, has occurred in both the Mississippi Valley area and the West. Deformation over at least a 77,000 square mile area occurred in connection with the 1964 Prince William Sound, Alaska earthquake. Deformation over a broad area also occurred in the 1811-1812 New Madrid earthquakes, mainly in the Reelfoot Lake area.

8) Aftershocks--A long aftershock sequence containing large earthquakes and many small ones and lasting for several years is typical of major earthquakes in the Mississippi Valley area. In the West, aftershocks typically die out after only a few months.

IDEAL AND ACTUAL TECHNICAL DATA BASES

An assessment of the nature and extent of earthquake hazards in the Mississippi valley area requires careful integration, analysis, and evaluation of all the available technical data (Hays, 1980, 1985). The objective of such assessments is to acquire a physical understanding of the earthquake process and to extract explicit answers to the questions:

1) Where have earthquakes occurred in the past? Where are they occurring now?

2) How big in terms of epicentral intensity and magnitude have past earthquakes been?

3) What physical effects (hazards) have past earthquakes caused? What was their extent spatially and temporally?

4) What were the causative mechanisms for each earthquake? Each hazard?

5) How often (on the average) do earthquakes of a given epicentral intensity and magnitude occur? How often (on the average) do specific hazards occur?

Once these questions have been answered satisfactorily, a technical basis exists for answering another question:

6) What are the viable options for mitigating the earthquake hazards of ground shaking, surface fault rupture, ground failure, and tectonic deformation? Which options are best?

The quantity and quality of the technical data are the two most important factors that facilitate making assessments of earthquake hazards and implementing loss-reduction measures. Table 1 gives a matrix showing the data requirements for a wide range of mitigation activities. If the technical data bases (described below) are "ideal," progress is rapid and controversy is minimal. The technical information is required on the following scales: 1) global (map scale of about 1:7,500,000 or larger to obtain the "big picture" of the global tectonic forces), 2) regional (map scale of about 1:250,000 or larger to define the physical parameters and their range of values that provide understanding of the spatial and temporal characteristics of earthquake activity in a region), 3) local (map scale of about 1:24,000 or smaller to determine the physical parameters and their range of values that control the site-specific characteristics of the earthquake hazards of ground shaking, earthquake-induced ground failure, surface faulting, tectonic deformation, and seiche and tsunami wave run up), and 4) engineering (map scale 1:1,000 or smaller that can be correlated with the spatial dimensions of specific structures, facilities, or lifelines). However, the actual data bases almost always have limitations in terms of scale. The challenge is to extrapolate beyond the limitations of the data and to use all the available data to answer the questions listed above in a reasonable but conservative manner. The ideal and actual data bases are discussed below:

1) IDEAL GEOLOGIC DATA BASE

The ideal data base consists of:

-- Maps showing the surface locations, types, and spatial extent of faults and other geologic structures in the region having seismogenic potential.

Objective: To establish the location, physical characteristics, and earthquake potential of the seismogenic sources in the region.

-- Logs and maps of trenches across specific fault zones, emphasizing detailed studies of the Quaternary and Holocene geology.

Objective: To establish slip rates and average recurrence intervals of major earthquakes on specific faults.

-- Maps showing the subsurface configuration of faults and structures having seismogenic potential.

Objective: To define the plastic-brittle zone of the crust and to quantify the fault rupture model.

-- Maps showing the geometry, thicknesses, and physical properties of the soil/rock columns in the region, including shear wave velocity and water content.

Objective: To define the wave propagation, site response, and soil failure models.

-- Maps of topography

Objective: To define the slope stability, a key parameter of the landslide model.

Limitations of the Actual Geologic Data Base: The actual geologic data base in the Mississippi Valley area has the following limitations:

-- The New Madrid seismic zone is not a fault that breaks the ground surface, but rather is a zone of buried rifting about 70 km wide and more than 200 km long having 2-3 km of structural relief (McKeown, 1984).

-- Knowledge of Quaternary and Holocene faulting is limited to a few sites in the Reelfoot Lake area where trenches have been excavated. These studies indicate an average recurrence interval of about 600 years for earthquakes large enough to produce ground motion strong enough to liquefy sand in the alluvium of the New Madrid region (McKeown, 1984).

-- The existence of the buried New Madrid seismic zone was inferred from gravity, aeromagnetic, seismic reflection, and seismicity data. Each type of data has uncertainties.

-- Knowledge of shear-wave velocities, thicknesses, and water content of the soil/rock columns is meager. Existing drill hole data are frequently considered to be proprietary and difficult to obtain.

-- Data on the local and engineering scales are meager.

2) Ideal Seismological Data Base

The ideal seismological data base consists of:

-- A reliable and complete catalog of pre-instrumental and instrumentally-located earthquakes containing the epicenter, hypocenter, size, and description of the ground-shaking and ground-failure effects.

Objective: To define where?, how big?, how often?, and what happened? in past earthquakes.

-- Maps of the historical and current seismicity.

Objective: To define where earthquakes have occurred and to delineate seismogenic sources more precisely.

-- Isoseismal maps of major earthquakes.

Objective: To define the damage distribution in past major earthquakes and to define an approximate seismic wave attenuation model.

-- Seismotectonic maps showing the relationship between earthquakes and geologic structures.

Objective: To define seismogenic sources.

-- Maps showing the distribution of stress in the crust and its correlation with geologic structures and the contemporary strain field.

Objective: To define the causative mechanism for earthquakes.

Limitations of the Actual Seismological Data Base: The actual seismological data base in the Mississippi Valley area has the following limitations:

-- Although the catalog is reasonably reliable and complete for earthquakes having epicentral intensities of VI or greater, the completeness of the historical records of seismicity is related to the settlement of the area and to the migration of settlers to the west with time. The seismicity is reasonably well known for nearly 200 years in the eastern part of the Mississippi Valley area, but for only about 100 years in the western part.

-- The regional seismicity network operated by St. Louis University was installed in 1974. Numerous microearthquakes have been recorded which have helped to define in detail the location of the New Madrid seismic zone. However, the network is inadequate to outline active faults and to provide seismotectonic correlations over the entire area.

-- Isoseismal maps for the 1811-1812 earthquakes were constructed in 1973 by Professor Nuttli of St. Louis University. These maps are uncertain to the west because of the lack of settlers in 1811-1812. Two of the best documented isoseismal maps are for the January 5, 1843, (I_o = VIII, m_b = 6.0) earthquake located near Memphis, Tennessee, and the October 31, 1895, (I_o = IX, m_b = 6.2) earthquake located near Charleston, Missouri.

-- A preliminary seismotectónic map was constructed by Heyle and McKeown in 1978. The average recurrence interval of great earthquakes in the New Madrid seismic zone, like those of 1811-1812, is estimated to be about 500-700 years.

-- Zoback and Zoback prepared a national map of the stress field in 1981. Additional data are needed to relate the current seismicity, existing stress field, and the prehistoric rifting precisely.

-- Data on the local and engineering scale are meager.

3) Ideal Engineering Seismology Data Base

The ideal engineering seismology data base consists of:

-- Strong motion records from earthquakes having magnitudes ranging from 5 to 8 or greater and epicentral distances ranging from the epicenter to at least 600 km. The records should include both free-field locations and building locations.

Objective: To define the amplitude, spectral composition, and duration of shaking for a wide range of magnitudes, epicentral distances, and site geologies.

-- Data on seismic wave attenuation.

Objective: To define frequency-dependent seismic wave attenuation functions.

-- Data on soil response.

Objective: To define frequency- and strain-dependent soil transfer functions. To determine linear and nonlinear behavior under different loads.

-- Data on building response.

Objective: To define how various types of buildings respond to a broad range of earthquake loads. To determine linear and nonlinear behavior under damaging loads.

-- Data on response of lifelines.

Objectives: To define how lifelines respond to a broad range of earthquake loads.

-- Data on damage distribution.

Objective: To develop fragility curves for a broad range of earthquake loads that can be used in loss estimation scenarios.

-- Lessons from past earthquakes.

Objective: To take advantage of the fundamental knowledge gained from the "laboratory" provided by a damaging earthquake to determine why structures of various types were and were not damaged.

Limitations of the Actual Engineering Seismology Data Base: A strong motion array of about 20 instruments has been deployed in the Mississippi Valley area. It is operated by St. Louis University. None of the engineering seismology data sets listed above have been acquired. A combination of theory and empirical procedures are used at the present time to devise criteria for earthquake-resistant design. Data from other locations (for example, California) are scaled to correspond to the seismotectonic parameters of the Mississippi Valley area.

CONCLUSIONS

The geological, seismological, and engineering seismology data bases of the Mississippi Valley area have definite limitations. Lack of data on the local and engineering scales is one limitation. However, they are adequate for: 1) creative research to resolve technical issues and 2) development and implementation of loss-reduction measures in the Mississippi Valley area. The opportunities for potential applications of technical data include: 1) hazards maps, 2) design criteria, 3) landuse, vulnerability, and loss studies, 4) guidelines for inspection and review of earthquake-resistant construction, 5) an agenda to guide public policy, education, and training programs, 6) response planning, and 7) postearthquake investigations and activities to transfer technology (see Figure 5).

A special word needs to be said about post earthquake investigations. They should be a key strategy in upgrading technical data bases in the Mississippi Valley area. Data from worldwide earthquakes should be used, especially for those areas having a similar tectonic environment as the Mississippi Valley area.

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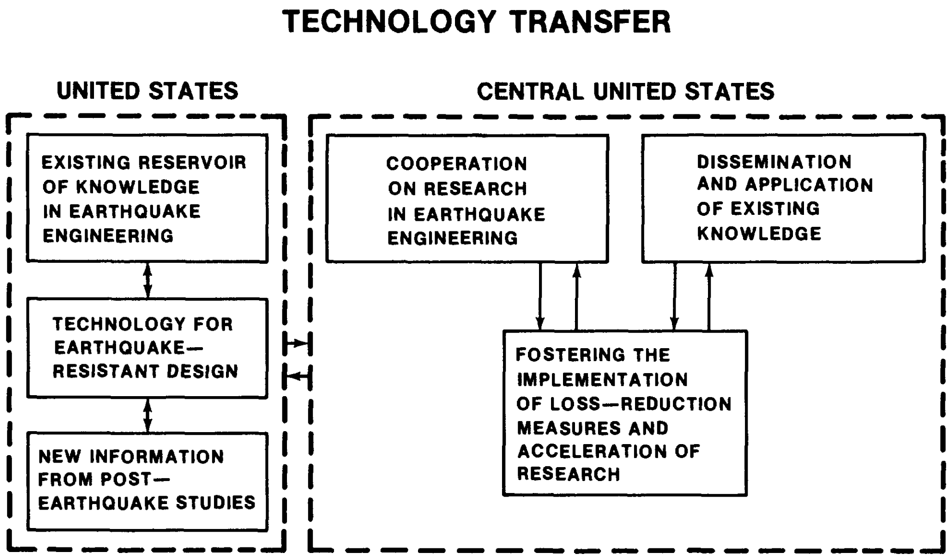

Figure 5.--Schematic illustration of the overall process of technology transfer. Appropriate technologies for earthquake hazards mitigation exist in other parts of the United States. They can be transferred, with fine tuning to the Mississippi Valley area. The goal is to accelerate progress in the mitigation of earthquake hazards in the Mississippi Valley area in the most cost-effective manner.

TABLE 1

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

EARTH SCIENCES DATA	RESPONSE PLANS				
1. Geologic Data - Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).	Regional response plan	State response plan	City response plan	Institution/business business response plan	Personal response plan
2. Seismological Data - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field					
3. Engineering Seismology Data - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution - Lessons from past earthquakes					

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

POLICY, EDUCATION, AND TRAINING

EARTH SCIENCES DATA						
1. Geologic Data - Faults (location, type, tectonic - history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).	Regional seismic safety organization	State seismic safety organization	University earthquake engineering curriculum	Professional development training	Public schools curriculum	Professionals geologists, seismologists, architects)
2. Seismological Data - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field						
3. Engineering Seismology Data - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution - Lessons from past earthquakes						

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

INSPECTION AND REVIEW

EARTH SCIENCES DATA	Earthquake Safety inspection of new/existing dam failure	Earthquake safety inspection for new/existing public buildings schools	Earthquake safety inspection for new/existing private buildings	Review of dams	Review of hospitals	Review of nuclear power plants
1. Geologic Data						
- Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) and surface faulting						
- Seismogenic zones (point sources, line sources, plan sources, area sources).						
- Slope stability						
- Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).						
2. Seismological Data						
- Seismicity (epicenter, focal depth, magnitude)						
- Intensity (isoseismal maps)						
- Stress field						
3. Engineering Seismology Data						
- Strong motion records (ground, buildings)						
- Seismic wave attenuation						
- Soil response						
- Building response						
- Lifeline response						
- Damage distribution						
- Lessons from past earthquakes						

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

LANDUSE/VULNERABILITY-LOSS

EARTH SCIENCES DATA					
1. <u>Geologic Data</u> - Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).	Design criteria for nuclear power plants (special regulations)	Seismic microzonation for land use planning	Vulnerability/loss study--maximum earthquake scenario	Vulnerability/Loss study--100 years exposure time scenario	Insurance considerations various exposure time and probabilities
2. <u>Seismological Data</u> - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field					
3. <u>Engineering Seismology Data</u> - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution -Lessons from past earthquakes					

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

DESIGN CRITERIA

EARTH SCIENCES DATA					
1. Geologic Data - Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content). 2. Seismological Data - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field 3. Engineering Seismology Data - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution - Lessons from past earthquakes	Design criteria for public buildings (codes)	Design criteria for private building (codes)	Design criteria for critical public facilities (city hall, EOC)	Design criteria for dams (special regulations)	Design criteria for hospitals special regulations

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

EARTH SCIENCES DATA	EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES				
1. <u>Geologic Data</u> - Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).	Maps of ground shaking	Maps of liquefaction susceptibility	Maps of landslide susceptibility	Maps of potential tectonic deformation and surface faulting	Map of potential inundation from dam failure
2. <u>Seismological Data</u> - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field					
3. <u>Engineering Seismology Data</u> - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution - Lessons from past earthquakes					

TABLE 1 (CONTINUED)

HAZARD MAPS

MATRIX OF EARTHQUAKE HAZARDS MITIGATION OPPORTUNITIES IN THE CENTRAL UNITED STATES AND THE REQUIREMENTS FOR EARTH SCIENCES DATA

AFTER THE EARTHQUAKE

EARTH SCIENCES DATA			
1. Geologic Data - Faults (location, type, tectonic history, cycle of earthquake activity, rupture length) - Seismogenic zones (point sources, line sources, plan sources, area sources). - Slope stability - Soil/rock column (types of soil and rock thicknesses, shear wave velocities, water content).	Post earthquake investigation plans	Redevelopment and recovery plans	Future mitigation plans
2. Seismological Data - Seismicity (epicenter, focal depth, magnitude) - Intensity (isoseismal maps) - Stress field			
3. Engineering Seismology Data - Strong motion records (ground, buildings) - Seismic wave attenuation - Soil response - Building response - Lifeline response - Damage distribution - Lessons from past earthquakes			

THE CURRENT AND PROJECTED STATE-OF-KNOWLEDGE ON EARTHQUAKE HAZARDS

by

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INTRODUCTION

The central United States is an area of low probability but high risk for earthquake damage. That is, damaging earthquakes occur infrequently but, when they do, they generally cause property loss over a large area of the country.

When speaking of damaging earthquakes it is necessary to distinguish between two types, depending upon their size. The first are moderate-sized earthquakes, of body-wave magnitude less than 6. The second are large earthquakes, of body-wave magnitude of 6 or greater. The former have damage areas of radius about 75 miles (120 kilometers) or less, with most damage being of the nonstructural or architectural type, whereas the latter result in damage areas with radius as large as 400 to 500 miles (650 to 800 kilometers) and result in significant structural damage, as well as injuries and loss of life.

In this presentation I shall briefly review the earthquake history of the central United States, show where earthquakes presently are occurring, describe the effects of past large earthquakes, and attempt to depict the consequences of both the moderate-sized earthquake and the very large earthquakes. Frequently I shall refer to magnitude scales, both body-wave (m_b) and surface-wave (M_S). The relation between them for the central United States is

m_b	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
M_S	2.8	3.3	4.3	5.3	6.3	7.3	8.3	9.0
maximum intensity	IV-V	V-VI	VI-VII	VII-VIII	VIII-IX	IX-X	X-XI	XII

In newspaper accounts and often in scientific or technical papers the so-called "Richter magnitude" usually is the larger of the two values. Thus for earthquakes of m_b no more than 5.7 it is the m_b value, and for earthquakes of m_b greater than 5.7 it is the M_S value. The m_b value is a measure of the amplitude of high-frequency ground shaking, whereas the M_S value is a measure of the amplitude of the low-frequency ground shaking. Modified Mercalli intensities of VI and VII usually are associated with non-structural or architectural damage, and M.M. intensities of VIII to XII with structural damage. Poor soil conditions can increase the intensity level by one to two units at the same distance from the earthquake epicenter.

EARTHQUAKE HISTORY OF CENTRAL UNITED STATES

The earthquake history of the central United States is dominated by the series of earthquakes that ruptured the New Madrid fauult in the winter of 1811-1812. On December 16, 1811 there were three very large earthquakes on the southern branch of the fauult in eastern Arkansas, extending from a point 25 miles (40 kilometers) northwest of Memphis to Reelfoot Lake in northwestern Tennessee (M_S of 8.6 at 2:30 am, M_S of 8.0 at 8:15 am, and M_S of 8.0 at noon). Together these three earthquakes ruptured the entire southern segment of the fault, of length about 90 miles (150 kilometers). On January 23, 1812 an earthquake of M_S equal to 8.4

ruptured the central segment of the fault, of length about 45 miles (75 kilometers). The largest of the earthquakes, with M_S of about 8.8, which occurred on February 7, 1812 near the town of New Madrid, ruptured the entire northern branch of the fault that is about 60 miles (100 kilometers) long. Between December 16, 1811 and March 15, 1812 there were in addition 5 earthquakes of M_S approximately 7.7, 10 of M_S about 6.7, 35 of M_S about 5.9, 65 of M_S about 5.3, and 89 of M_S about 4.3 (m_b = 5.0). The smallest of these earthquakes had a magnitude equal to that of the northeastern Ohio earthquake of January 31, 1986, and just slightly smaller than that of the north central Kentucky earthquake of July 27, 1980 (m_b = 5.2). The latter caused several million dollars worth of property damage. The area of intensity VI or greater for the M_S = 8.4 earthquake of December 16, 1811 is estimated as 800,000 square miles (2,000,000 km^2) and of intensity VIII or greater as 100,000 square miles (250,000 km^2). Eighteen of the earthquakes were felt as far away as Washington, D.C. This series of earthquakes is the most awesome in the history of the United States.

Since 1812 there only have been two large earthquakes, of M_S greater than 6, in the central United States. Both occurred on the New Madrid fault. That of January 4, 1843 had its epicenter in Arkansas at the extreme southern end of the fault, about 25 miles (40 kilometers) northwest of Memphis. It did structural damage in Memphis, southwest Tennessee, northeast Arkansas and the extreme northwest corner of Mississippi. Its M_S value was approximately 6.3, and the area of intensity VI or greater was about 60,000 square miles (160,000 km^2). On October 31, 1895 an M_S = 6.7 earthquake occurred near Charleston, Missouri, near the northern end of the New Madrid fault. Structural damage occurred in the surrounding area of Missouri and in a narrow band of northern Kentucky and southern Illinois bordering the Ohio River, eastward to near Evansville, Indiana. The area enclosed by the VI isoseism was approximately 125,000 square miles (300,000 km^2). Chimneys were toppled in St. Louis, and walls and foundations of masonry buildings cracked there.

Seventeen moderately large earthquakes, of m_b 5.0 to 5.8 (M_S of 4.3 to 5.9) occurred in the central United States in historic times in addition to the 189 of that size in the 1811-1812 New Madrid series. Figure 1 shows the location, magnitude and source zone of these 17 events. Of them only two were on the New Madrid fault, one near the town of New Madrid and the other at Marked Tree, Arkansas, near Memphis. Two were in the Wabash Valley, a region where focal depths are typically about 20 kilometers, suggesting the possibility of occurrence of a very large earthquake there. Two were in the Illinois Basin of southern Illinois and one in northern Illinois. The two earthquakes in northwestern Ohio, near the town of Anna, are noteworthy for relatively shallow depths of no greater than 5 kilometers, which possibly limits the maximum earthquake in the region to about the size of the 1875 and 1937 earthquakes. The same may hold true for the 1980 earthquake in north central Kentucky and the 1986 earthquake in northeastern Ohio. One of the 17 earthquakes was in the St. Francois uplift region to the northwest of the New Madrid fault. Two of the earthquakes, which appear to be associated with the Ouachita-Wichita Mountains zone, had felt areas and depths which suggest that the region may be capable of producing large earthquakes. The same statement likely applies to the two earthquakes associated with the Nemaha Uplift. Finally, the one earthquake in the Colorado Lineament zone is fairly shallow, suggesting that the biggest earthquakes for that

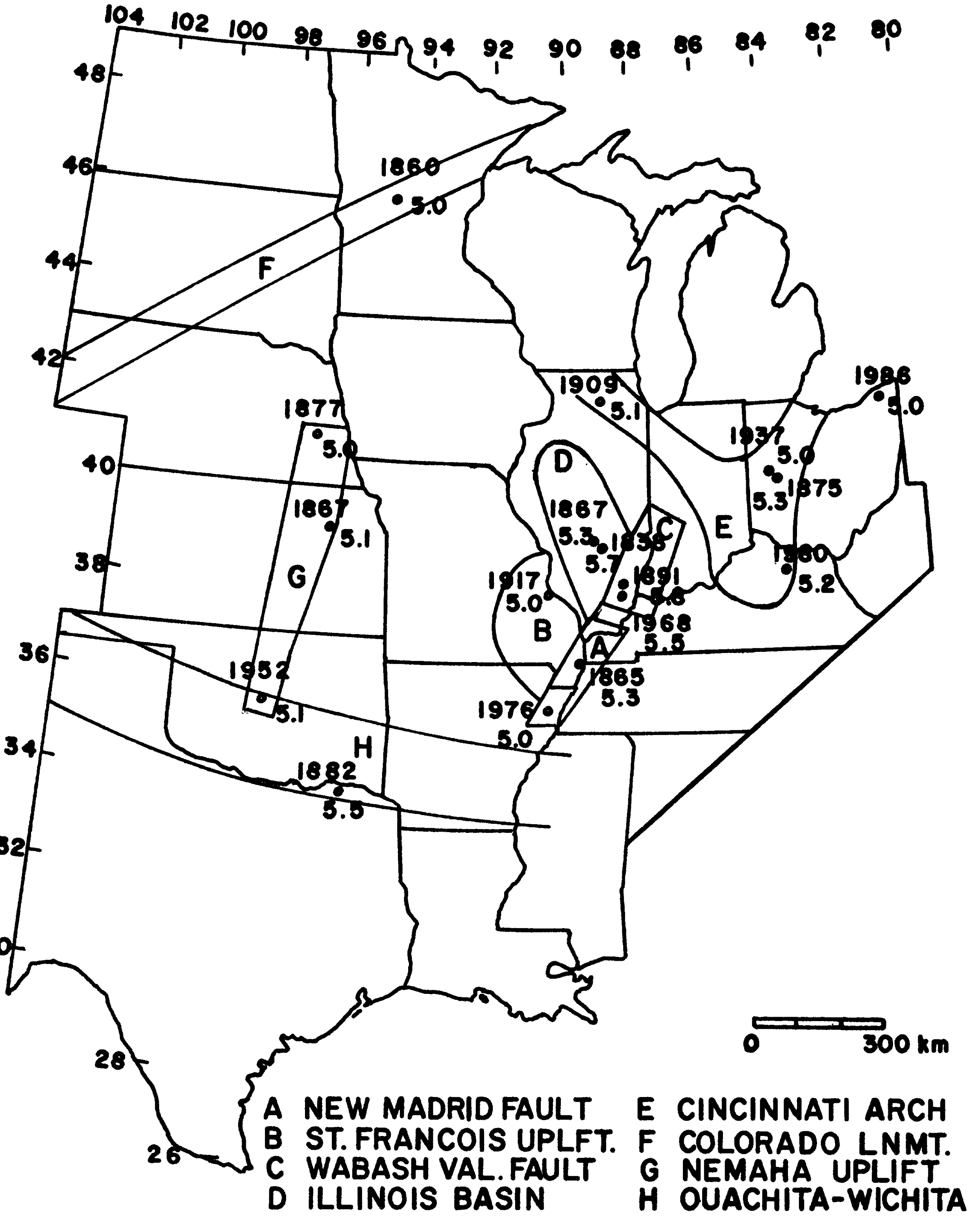


Fig. 1. Location of moderately large central United States earthquakes, of m_b 5.0 through 5.8, that occurred since 1812. The larger magnitude New Madrid earthquakes of 1811, 1812, 1843 and 1895 are not included in the figure.

region will not be major ones. The source zone boundaries were drawn on the basis of historical and instrumental seismicity (including microearthquakes). Of the eight source zones shown in Figure 1, shallow focal depths and thus magnitudes not greater than about 5.5 likely are the rule for the Cincinnati Arch and the Colorado Lineament. Great earthquakes have occurred along the New Madrid fault and very large ones may occur along the Wabash Valley fault, both regions of crustal rifting. The remaining source zones appear to have the potential for producing large earthquakes, of M_S about 6.5 to 7.0.

EARTHQUAKE RECURRENCE RATES

Seismicity catalogs can be used to estimate recurrence rates in the central United States. The solid-line curve of Figure 2 shows the cumulative number of earthquakes in the area for the interval 1812 through 1977, excluding aftershocks and treating the 1811-1812 series to be equivalent in energy release to a single earthquake of m_b about 7.4 to 7.5. The figure shows that the 1811-1812 sequence has a recurrence time larger than 165 years, which explains why the points for $m_b = 6.6$ and 7.3 lie above the curve. There also appears to be a deficiency of earthquakes in the m_b range of 5.1 through 5.5, which may be real or may be because of difficulties in assigning magnitudes to non-instrumentally recorded earthquakes. The equation of the solid-line curve of Figure 2 is $\log N = 4.60 - 1.03\, m_b$, where N is the number of earthquakes per year in the central United States of magnitude greater than or equal to m_b. Recurrence times, in years, for selected values of m_b, are:

m_b	≥ 7.2	≥ 6.6	≥ 6.0	≥ 5.5	≥ 5.0
recurrence time					

(years)	655	158	38	12	3.5

Earthquakes of m_b = 7.2 would correspond in size to the 1811-1812 New Madrid events, of m_b = 6.6 to the Charleston, South Carolina earthquake of 1886, of m_b = 6.0 to the 1843 and 1895 New Madrid events, of m_b = 5.5 to the 1968 south central Illinois and the 1982 New Brunswick earthquakes, and of m_b = 5.0 to the 1980 north central Kentucky and 1986 northeastern Ohio events.

The dashed line curve of Figure 2 is a cumulative recurrence curve for the mainshocks and aftershocks of the 1811-1812 events in the three-month period December 16, 1811 through March 15, 1812. It shows that in that three-month interval there were approximately ten times the number of earthquakes, for any given magnitude, as for all the central United States mainshocks in the 166-year interval of 1812 through 1977. Roughly speaking, 97% of the energy released by earthquakes in the central United States since 1811 happened during the winter of 1811-1812.

GROUND SHAKING AND DEFORMATION IN PAST EARTHQUAKES

The 1811-1812 mainshocks produced massive ground deformation over a wide area. Sand craters and sandblows, some of which still can be seen, occurred in the Mississippi River flood plain from south of St. Louis to the mouth of the Arkansas River, in the Ohio River valley from Cairo, Illinois to southwestern Indiana and in the St. Francois River valley of Arkansas. Liquefaction and landslides affected an area of about 6,000 square miles (15,000 km^2) in southeast Missouri, western Tennessee and northeastern Arkansas. Vertical uplift and subsidence of 10 to 20 feet was reported in the epicentral areas, as well as deep and long rifts in

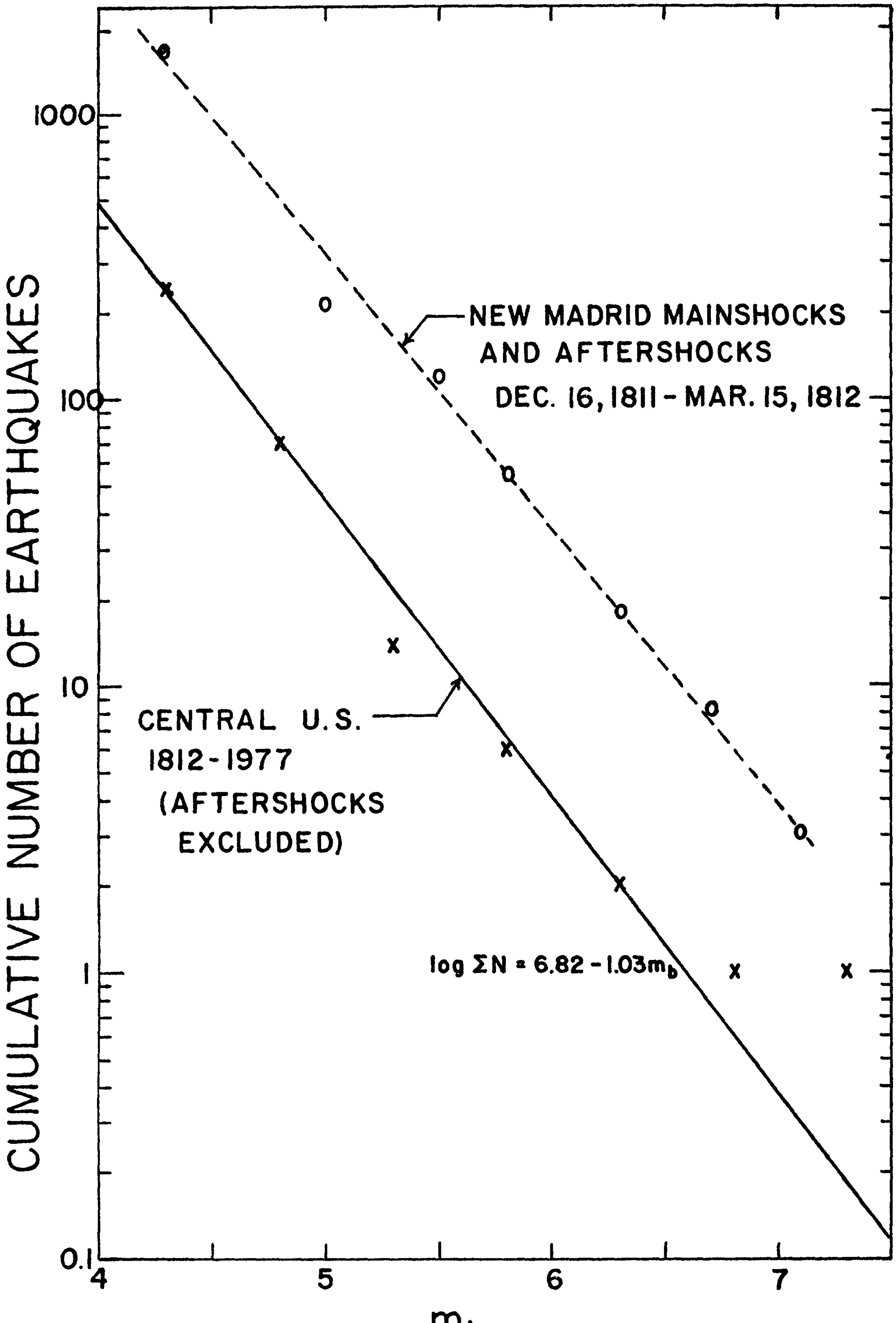


Fig. 2. Cumulative number of earthquakes versus body-wave magnitude. The solid-line curve applies to all the central United States earthquakes from 1812 through 1977, excluding aftershocks, and considering the 1811-1812 earthquakes as equivalent to one mainshock of m_b = 7.4 to 7.5. The dashed-line curve shows the number of earthquakes that occurred in the first three months of the 1811-1812 series. Aftershocks continued through ~~at least~~ 1819.

the soil that were so wide that they could not be jumped across on horseback. At St. Louis, at least 175 miles (280 kilometers) from the mainshock epicenters, 2 to 3 feet thick stone foundations of houses were split by the ground shaking and chimneys fell. Similar damage occurred at Louisville, at about the same epicentral distance. Low density of population and simple log cabin structures accounted for the relatively small loss of life and property, although the area of southeast Missouri was so ravaged by the earthquakes that the U.S. Congress passed the first Disaster Relief Act in 1815, giving new land to the settlers of the area.

The only other central United States earthquake known to have caused notable ground failure was the Charleston, Missouri event of October 31, 1895. A new lake was formed and sandblows were reported in an area of about 6 miles (10 kilometers) radius. Building damage was extensive at Charleston, Missouri, and hundreds of chimneys were shaken down in nearby Cairo, Illinois.

Chimney damage occurs commonly in the central United States for earthquakes of m_b = 5.0 or greater. For the great 1811-1812 earthquakes such damage was observed as far away as 350 miles (650 kilometers). For the 1843 earthquake, at the southern end of the fault, chimneys were thrown down in Memphis, and damaged in Nashville, St. Louis and Helena, Arkansas. For the 1895 earthquake, near the northern end of the New Madrid fault, chimneys fell at Paducah, and were damaged in Memphis and St. Louis. For earthquakes of m_b = 5.0 to 5.5 chimney damage generally is confined to one or a few counties, near the epicenter.

CONSEQUENCES OF A MAJOR EARTHQUAKE IN THE CENTRAL UNITED STATES

Within the past ten years a number of reports were written that assessed the impact of major earthquakes on metropolitan areas, most of them in the western United States. However, several addressed the effects of earthquakes on the New Madrid fault. The latest of these, which was done under the auspices of the Federal Emergency Management Agency, usually is referred to as the Allen-Hoshell report. It was released in October 1985, just a month after the disastrous Mexican earthquake. The consequences of major earthquakes, as described in terms of loss of life, injury, and economic loss due to building damage, are not pleasant to contemplate. However, the future bodes even worse as man continues to concentrate in metropolitan areas and adopts a lifestyle that is dependent on undisturbed and uninterrupted access to lifelines.

All of the assessments of earthquake consequences essentially are based upon empirical data obtained from western United States earthquakes. The studies have three elements in common: 1) A map is prepared showing the distribution of either MM intensity or peak ground motions for an earthquake of an assigned magnitude located at a particular place. Usually the assigned magnitude is the largest to be expected for the region, and its epicenter or location is taken to be that which will have the maximum impact on the area. 2) An inventory is made of all buildings in the area that will be affected, taking into account their location, size, type of construction, usage, population density, cost, and other relevant factors. 3) Using data from western United States earthquakes that relate MM intensity or peak ground motions to damage for various types of structures and construction practices, damage estimates are made. Actual studies of this type can involve a high degree of sophistication that is not evident in this simple outline.

The experience of Mexico City with regard to the $M_S = 8.1$ earthquake of September 19, 1985, however, must cause us to ask if the above-mentioned loss estimates for New Madrid earthquakes may not be too low. Mexico City is 250 miles (400 kilometers) from the epicenter of the earthquake. Assuming that it was a subduction-type earthquake, further study may show that the fault might have had several rupture points, some closer to Mexico City than the point at which the rupture initiated, but still at least 200 miles (350 kilometers) from Mexico City. The part of Mexico City that suffered most of the damage and loss of life is built on a dried-up lake bed, which is a rather unique situation. Figures 3, 4 and 5 are copies of strong-motion records given to me by Prof. George W. Housner of the California Institute of Technology. Figure 3 contains the three-component accelerograms recorded on firm ground at the Institute of Engineering of the City University, UNAM. Maximum acceleration was 3.9% g (3.9% of the acceleration of gravity or 38 cm/sec^2). Figure 4 contains the three-component accelerograms at a site on the old lake bed near the Communications and Transportation Building. Maximum acceleration, on the east-west component, was 17% g. On the north-south component it was 10% g, and on the vertical component 3.6% g. Important features are the long duration of strong shaking, about 40 seconds, and the wave periods of 1 to 2 seconds (frequencies of 1 to 0.5 Hz). The wave periods are near the natural or resonant periods of 10 to 20 story structures, those that suffered the most damage. Figure 5 shows the north-south component accelerogram of Figure 4, along with its integrated velocity and displacement records. The maximum ground

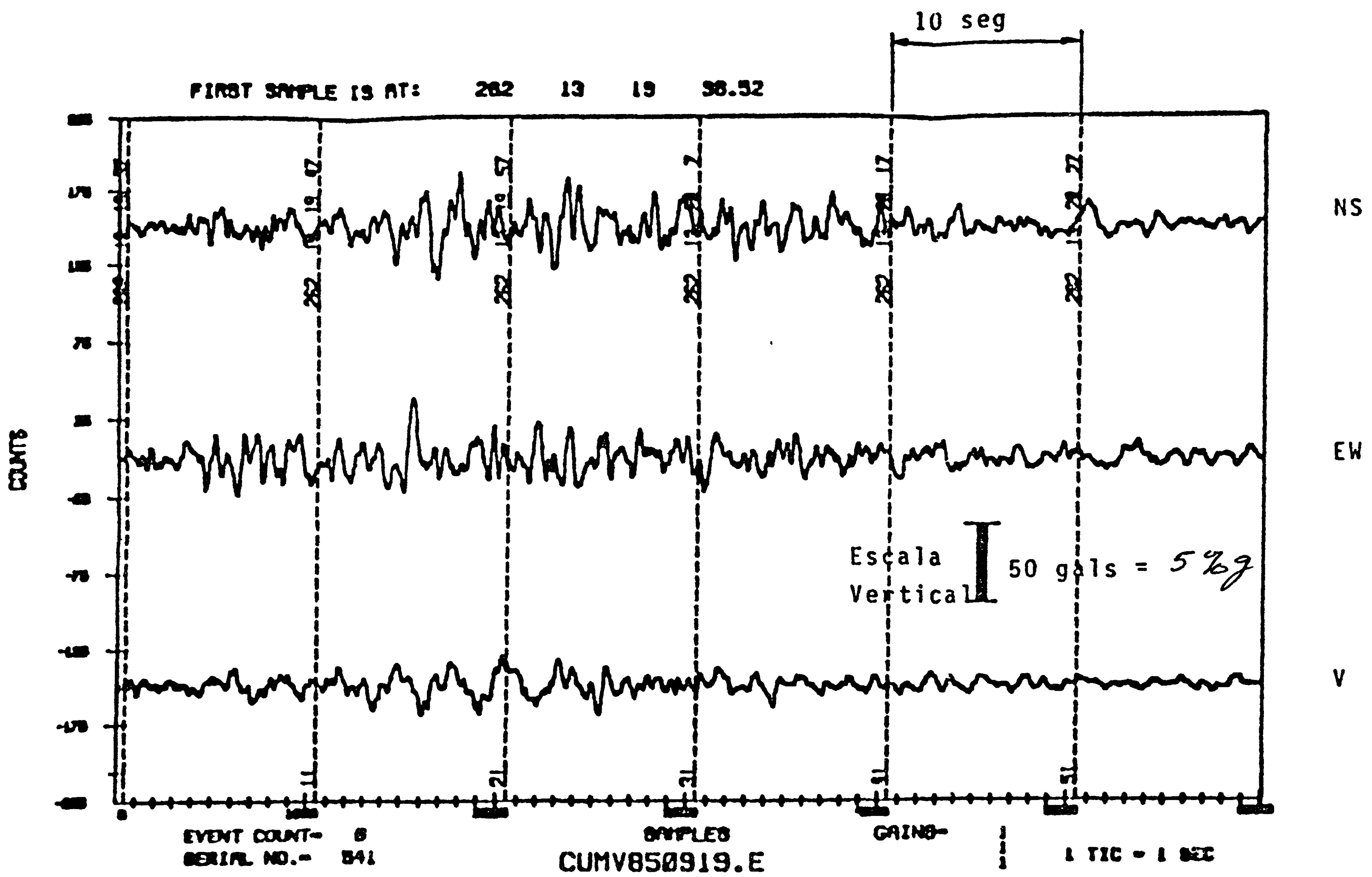


Fig. 3. Three-component accelerograms obtained from a firm ground site in Mexico City (epicentral distance = 400 km) at the Institute of Engineering of UNAM, City University for the September 19, 1985 earthquake of M_S = 8.1. Peak acceleration was slightly less than 4% g. Wave periods as long as 3 sec are visible. (Accelerogram copy provided to Prof. George W. Housner from UNAM.)

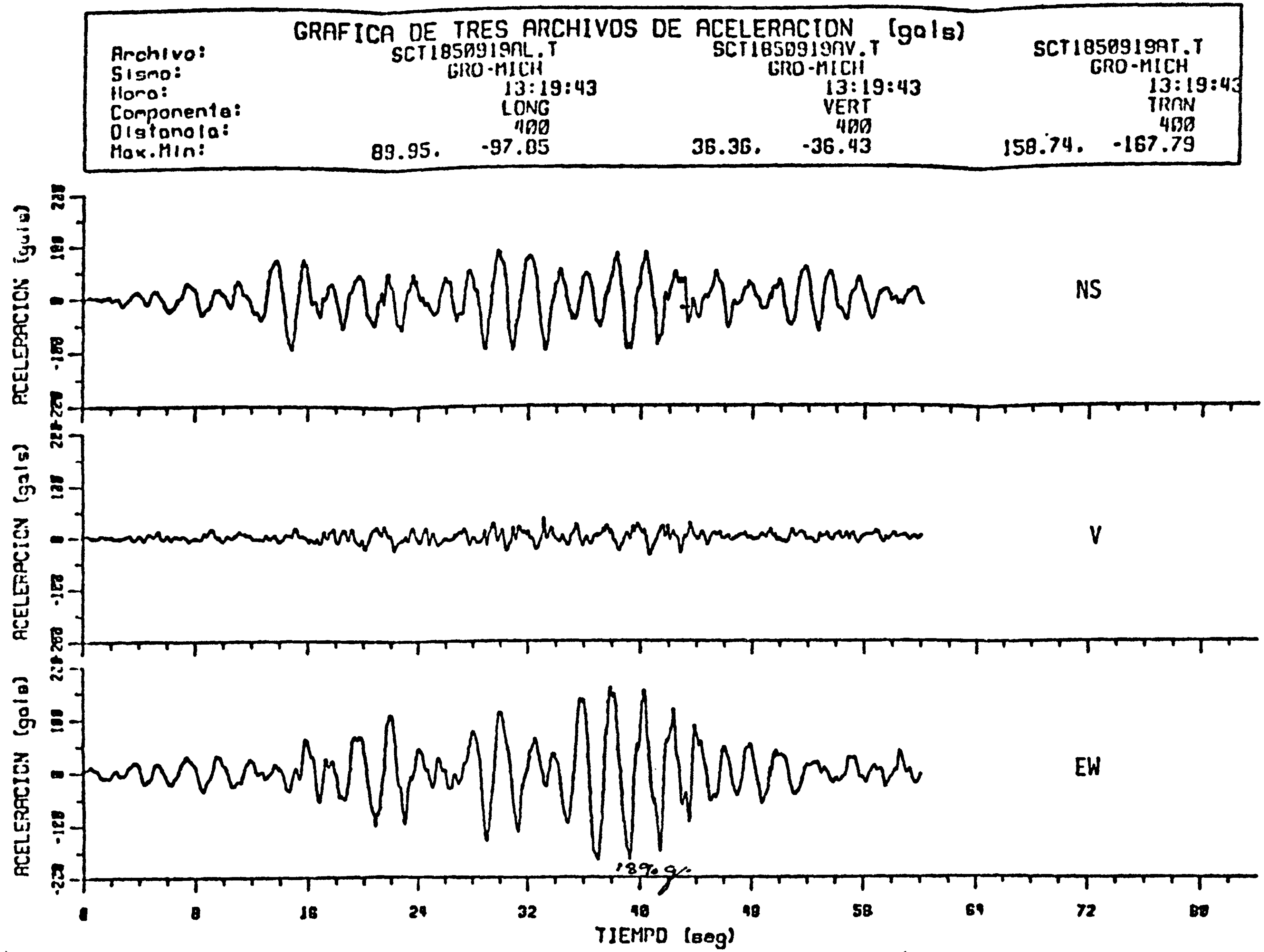


Fig. 4. Three-component accelerograms obtained from a site in Mexico City (epicentral distance = 400 km) on the old lake bed near the Communications and Transportation Building for the September 19, 1985 earthquake of M_S = 8.1. Peak acceleration, on E-W component, is approximately 17% g. Large amplitude, 2-sec period waves on the N-S component have a duration of approximately 40 sec. (Accelerogram copy provided to Prof. George W. Housner from UNAM.)

SISMO	GRO-MICH	REGISTRO	SCT1850919AL.T	CORRECCION	
DATOS	IDEI	ESTA	SCT1	METODO	CALTECH.
FECHA	850919	INST	03-144	FILTRO	0.070 0.100 23.0 25.0
HORA	13:19:44	COMP	LONG	ΔT	0.010
EPIC	17.680 102.470	HORA	13:19:43	MAX ACEL	89.95. -97.85
M	7.0	DUR	59.99	MAX VEL	38.68. -33.75
H	33	DIST	400	MAX DESP	17.40. -14.29

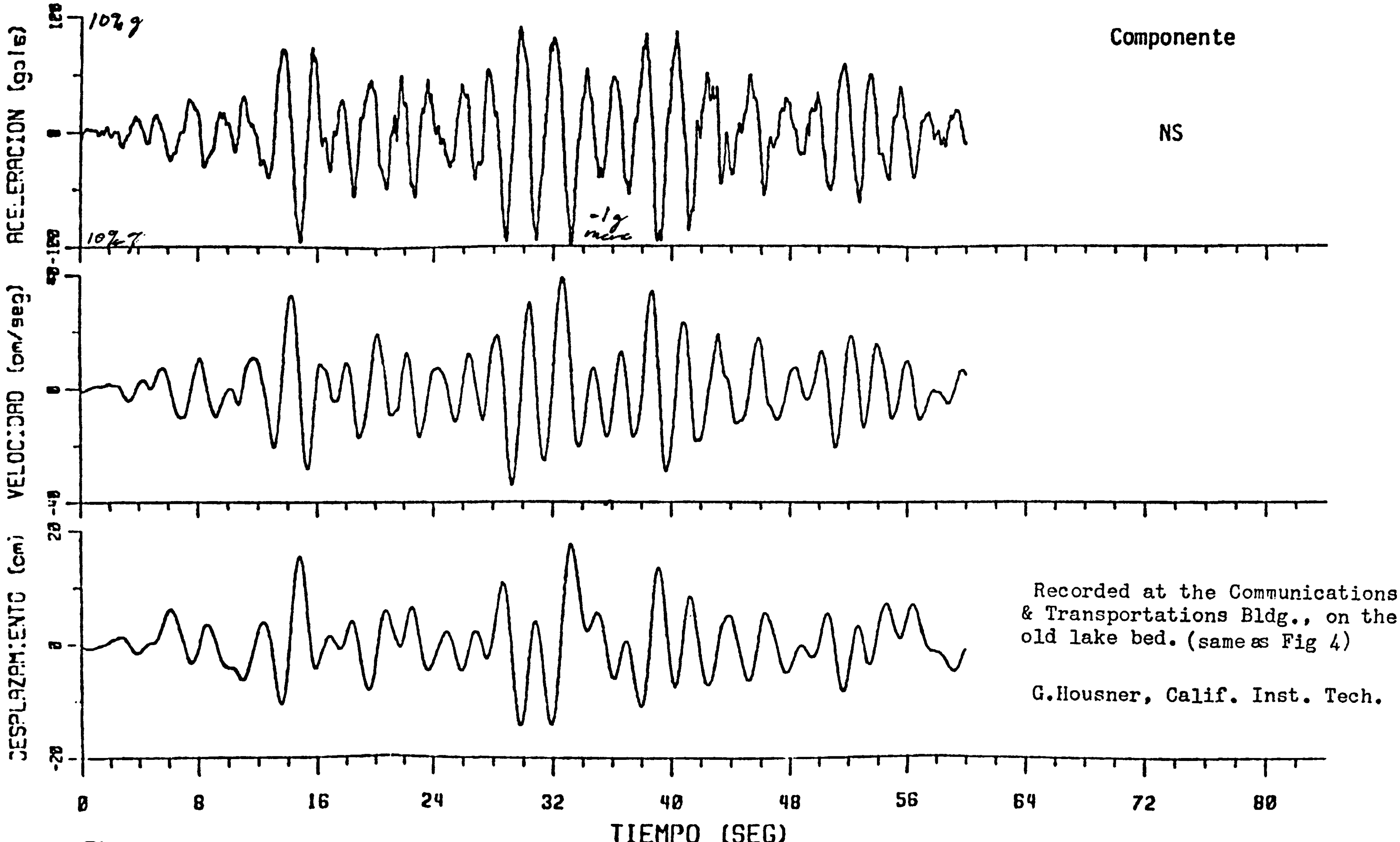


Fig. 5. N-S component accelerogram of Fig. 4, along with the integrated velocity and displacement records obtained from it. Maximum velocity on this component was 39 cm/sec and maximum displacement was 17 cm.

(Copy of strong-motion records provided to Prof. George W. Housner from UNAM.)

velocity was 39 cm/sec and the maximum displacement 17 cm. Notice again the long duration of strong shaking and the relatively low frequencies of the wave motion.

What is the relevance of the Mexico City experience to the central United States? The latter area does not contain cities built on dried-up lake beds that might be subjected to resonant vibrations from a large earthquake. However, for different reasons, in the central United States long duration ground shaking of periods 1 to 3 seconds can be experienced at large distances. Unfortunately, anelastic attenuation of wave energy in this period range is extremely small in the central United States, which means that the ground shaking does not diminish rapidly as the distances increase, unlike the western United States and most earthquake-active regions. In addition, as the waves travel out from the epicenter they spread out in time, or disperse, which means that the duration of ground shaking gets larger as the distance from the epicenter gets larger. Figure 6 shows portions of two seismograms recorded at the Saint Louis University stations SLM and FVM, at a distance of about 500 miles (850 kilometers) from the Ohio earthquake of January 31, 1986. The upper trace is the record of a vertical component, broad-band instrument. It shows one packet of large amplitude waves, about 30 seconds in duration, of period near 1 second. Following this ia a packet of about 60 seconds in length, with wave periods near 2 seconds. The lower trace is of a vertical component instrument that emphasizes ground motion at periods near 1 second. On it can be seen at least 3 minutes of large motion at periods near 1 second. All of these large motions are associated with the type of surface wave called a Rayleigh wave. The horizontal component seismograms also show large

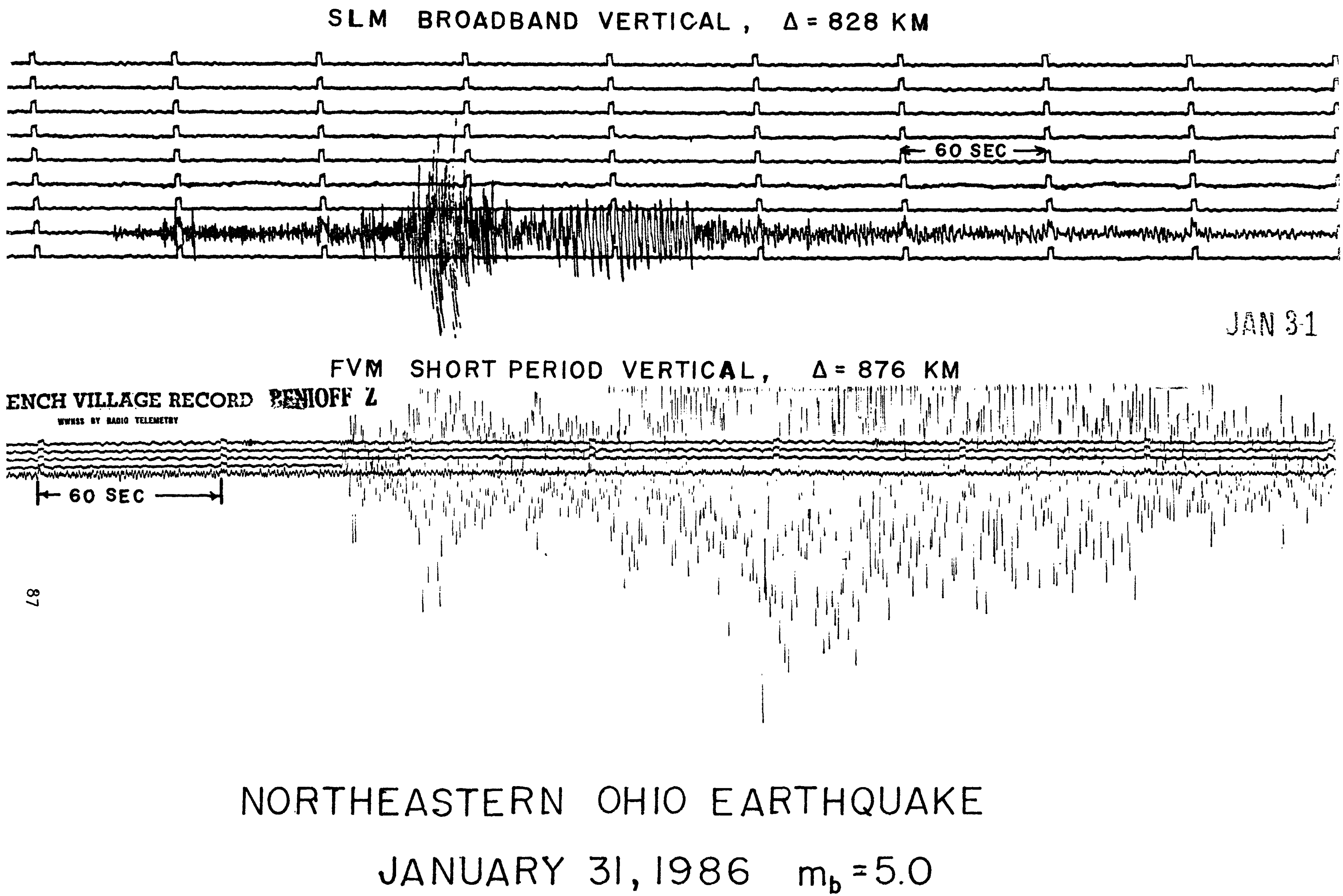
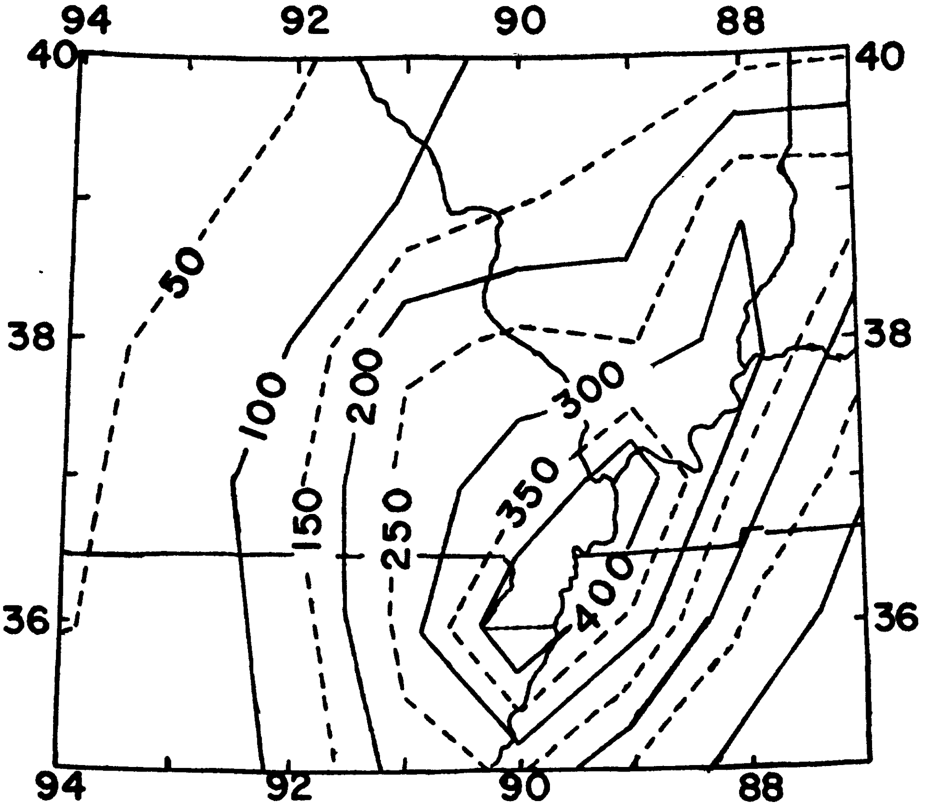


Fig. 6. Seismograms of Saint Louis University stations for the northeastern Ohio earthquake of January 31, 1986. Note the long duration of the surface waves, of period 1 to 2 sec.

amplitude and long duration shaking caused by both Rayleigh and Love waves. Even though this earthquake was only of $m_b = 5.0$, news media reported that the occupants of the upper levels of tall buildings in Chicago (distance of 350 miles or 550 kilometers) were made dizzy by the swaying.

Thus we have established that sites hundreds of miles from the epicenter of an earthquake in the central United States can experience large ground shaking of 1 to 3 minutes duration due to surface waves of period 1 to 3 seconds. The effects are similar to those observed on the lake bed of Mexico City, but for different reaasons. Next we must ask how large the motions in the central United States can be. In particular, can they be similar in size to those experienced in Mexico City? Figure 7 shows a map of ground acceleration for the central Mississippi Valley that has a 10% probability of being equalled or exceeded in a 100-year time period. The units are cm/sec^2, which if divided by 9.8 give the acceleration in percent of g. Note that at St. Louis the value on the map is between 15 and 20% g, almost identical to that observed in Mexico City on the lake bed. The metropolitan St. Louis area has hundreds, or perhaps a few thousand, 8 to 20 story buildings of various types and quality of construction.

I am not predicting that a major earthquake in the central United States will produce catastrophe similar to that in Mexico City for metropolitan areas hundreds of miles distant from the epicenter. What I wish to say is that many of the conditions responsible for the Mexico City disaster exist in our part of the country, but for different reasons. I believe it is prudent for us to investigate these conditions carefully, to con-



PEAK HORIZONTAL ACCELERATION (CM/SEC²) THAT HAS A 10% PROBABILITY OF BEING EQUALED OR EXCEEDED IN 100 YEARS

Fig. 7. Map of portion of central Mississippi valley showing peak horizontal acceleration values that have a 10% probability of being equaled or exceeded in any 100-year time interval.

sider them in any future studies of assessment of damage and loss of life, and, if necessary, to take remedial steps to prevent such a tragedy from happening.

AVAILABILITY AND APPLICATIONS OF EARTH SCIENCES DATA AT NATIONAL, REGIONAL, AND COMMUNITY SCALES

by

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INTRODUCTION

Many earth scientists spend most of their professional careers immersed in the analysis of the scientific and technical data of their discipline. They communicate routinely with other scientists, but little with others outside their field. This may be perfectly acceptable in some disciplines, but because of the life-threatening aspect of earthquakes and their potential for massive socio-economic disruption, seismologists and other earth scientists have an obligation not only to communicate new knowledge to the public but also to help formulate and implement mitigation measures based on this knowledge. In this report I will briefly examine how some earth sciences data are now or could be applied in the future to enhance seismic safety.

NATIONAL SCALE

On the national scale the quantitative assessment of seismic hazard is of extremely high priority, mainly because siting and design decisions for major critical facilities such as nuclear power generating plants or hazardous waste disposal sites will often be controlled by the estimated seismic hazard level. For example, probabilistic hazard studies undertaken by Lawrence Livermore National Laboratory and by the Electric Power Research Institute have augmented the ongoing work of the U.S. Geological Survey. Such research is important for reasons other than safety; the utility bills for all of us have risen because of the stringent seismic design criteria for nuclear plants and in some cases hydroelectric dams. It may well be that construction is overly conservative, but until this can be conclusively demonstrated with seismological and geological data, costly design requirements cannot be relaxed.

What are the data that are useful in seismic hazard analysis at the national scale? It turns out that quite different information is required for the western U.S. than for the East. In the West most (but not all) potential seismogenic zones can be delineated by careful geologic mapping of surface faults. Their maximum earthquake potential can be estimated from developed fault characteristic-magnitude relationships, and in some cases such as the southern San Andreas, recurrence intervals and their variance can be determined from paleoseismic studies. With this detailed seismic data in hand, quite sophisticated probabilistic analysis techniques can be (and have been) applied for hazard estimation, yielding input hazard information that is precise enough to be useful for planning purposes.

In the central and eastern United States, the fundamental problem is that earthquakes cannot be associated with known and mappable faults or surface geologic features. Aside from the spatial problem this causes in defining the limits of seismogenic zones, it also means that there is little or no geologic data from which to estimate the recurrence time of large, destructive earthquakes. One must resort to the historical seismicity record which is much too short and incomplete to yield accurate seismic hazard forecasts.

Thus we see that the problem of availability and application of earth sciences data at the national scale naturally divides into quite different problems at the regional scale.

In the West (west of the eastern front of the Rocky Mountains), there is an abundance of data available for detailed studies. Major advances will, I believe, be in the specialties of modeling near-field, short period strong ground motion, more accurate mapping and modeling of (non-linear) soil/site response to strong ground motion, and ultimately earthquake prediction.

For the East the state-of-art is at a much more rudimentary level. Major advances will require a much better understanding of the earthquake generation process in stable continental crust. Knowledge of the interplay of parameters such as the prevailing stress regime, rate of strain accumulation and failure criteria that are dependent on temperature, pressure and rock type is critical. Seismic hazard estimation, which is an essential prerequisite to effective mitigation and preparedness, therefore suffers from a much more poorly constrained data base in the East than in the West. The effect of this greater degree of uncertainty on regional and community mitigation and preparedness efforts will be examined next.

REGIONAL SCALE

At the regional scale (which I take here as a several state area), seismic hazard is at the level of being controlled by one or at most a few source zones. It is at this scale that the link between the seismic properties of a source zone and the expected level of strong ground motion at a particular locale becomes extremely important.

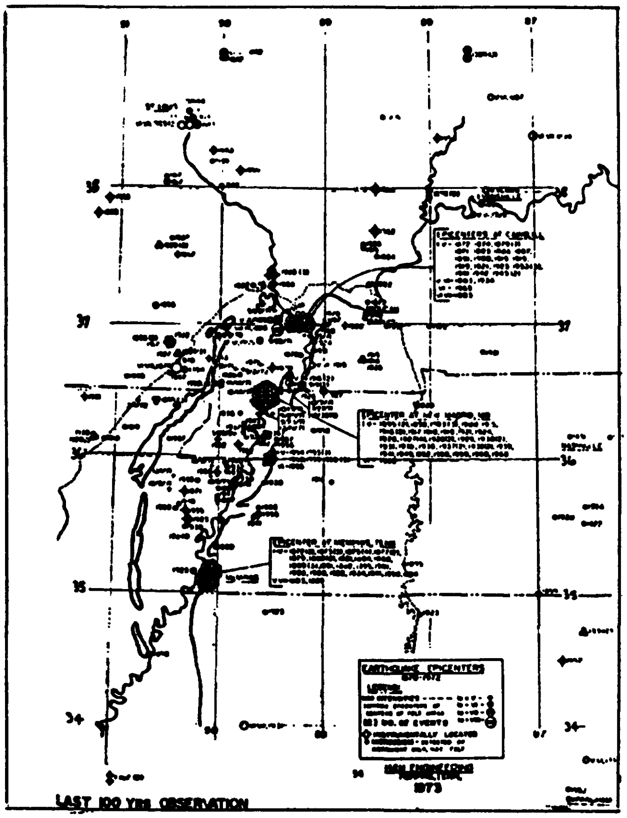
For example, even if you know that a seismic zone will produce a magnitude 6.5 event, the level of ground shaking, the frequency and the duration can be very different depending on whether the site is located in the Midwest, the Gulf Coastal Plain or on the Atlantic seaboard. Building and lifeline construction requirements will depend on the ability to accurately specify these parameters, which in turn requires accurate information on the regional attenuation properties of the crust. Even though such data are now available, it is at a scale such that much interpolation is required. Moreover, the effects of regional variation of crustal properties on frequency and duration are largely unknown. These two parameters played a key role in the extensive building damage and consequent loss of life in last fall's Mexico City/Michoacan earthquake.

Regional considerations are also important in the accurate specification of seismic source zones. Reelfoot rift/New Madrid serves as a good example. Prior to the installation of a high quality seismic instrument network in the mid-1970's, the historical seismicity associated with the zone was just a diffuse blob, with obvious population bias of epicenters (figure 1a,b). Just 10 years of seismic monitoring have greatly clarified the extent and activity of the zone (figure 1c) and stimulated a wide variety of basic research in such earth science disciplines as geology, seismology and geophysics. These efforts have led to a model for the evolution and present-day reactivation of the Reelfoot rift as the focus of the New Madrid seismicity, one of only a very few places in the central/eastern United States where this is possible. Delineation of the rift structure has allowed the source zone for large New Madrid earthquakes to be localized, thereby greatly improving the quantitative estimation of seismic hazard in the region.

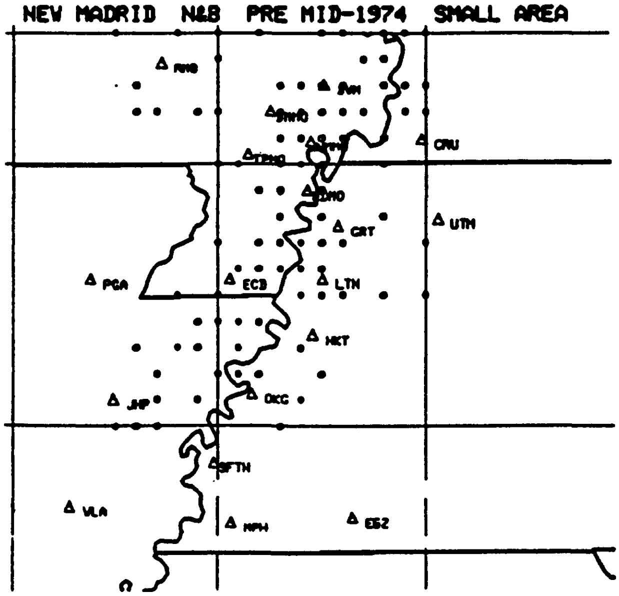
COMMUNITY SCALE

I will use Memphis, Tennessee to illustrate several earth science data applications at the local scale. Although communities and community problems are diverse, much in the approaches to dealing with seismic risk is transferable.

Memphis, Tennessee, is the most vulnerable (highest seismic risk) metropolitan area in the eastern United States. This fact has been clearly demonstrated in two recent analyses [Applied Technology Council, 1978; Algermissen et al., 1982]. Projected casu-



(A)



(B)

(C)

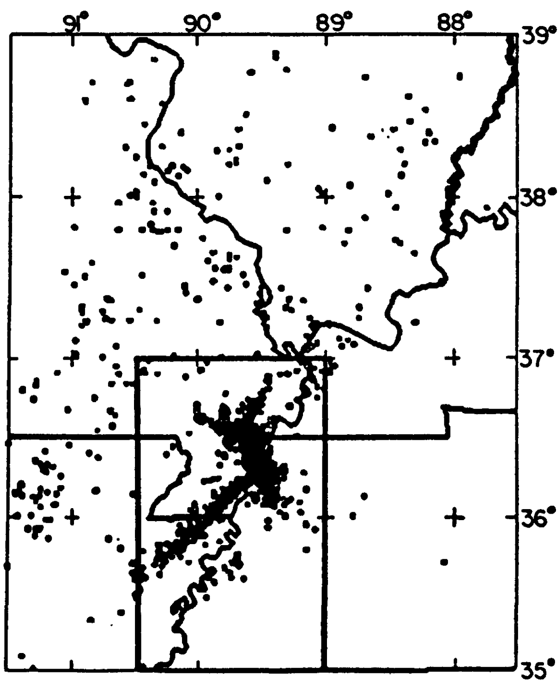


Figure 1. The New Madrid seismic zone, central United States. (A) Historical seismicity; (B) Pre-1974, twentieth century; (C) 1974-1983, good instrumental coverage.

alties and loss estimates from a large earthquake are extremely high [FEMA, 1985] as are projected costs of implementing seismic building code provisions [BSSC, 1985]. Thus problems encountered by Memphis are instructive, if somewhat amplified, for application in other communities.

(1) *Seismic Building Code Implementation.* The design of a methodology for a comprehensive cost/benefit analysis of all aspects of seismic building code implementation in eastern U.S. cities is an essential applied technology objective. Future projections of costs and benefits for as long as a century will be important.

Using Memphis as an example, a Building Seismic Safety Commission study of the cost impact of the ATC 3-06 recommended code provisions found that estimated changes in structural costs would average 18.9% (total costs of +5.2%), more than double the next closest city (New York) in which trial design tests were conducted [BSSC, 1985]. The high implementation cost may be attributed to the unconsolidated soil base, the lack of any current seismic requirements and a relatively low lateral wind load (e.g., ~80 mph as compared to hurricane-track cities such as Charleston, SC at ~125 mph).

The implications of such a cost increment on construction practices and the overall economy are largely unknown but sensed to be profound. Accurate projections will require a range of expertise in hazard assessment, earthquake engineering, urban planning and economics.

The city of Memphis has been considering the adoption of seismic code provisions for more than a year now through an appointed Seismic Building Code Provisions Committee (see the report by W. Howe, this volume). It is likely that the question of code adoption will be vigorously debated in Memphis during the next several years and that Memphis may well serve as a prototype for other eastern cities. Thus data gathered pertaining to consequences of code implementation will carry immediate and direct relevance to a major societal problem elsewhere in the eastern U.S.

(2) *Liquefaction/Paleoseismicity.* As in the rest of the central and eastern U.S., the seismogenic faults of the New Madrid seismic zone have no surface expression. The fruitful geomorphological techniques for estimating fault slip rates for application to seismic hazard analysis in regions like Japan [Wesnousky et al., 1984] and California [Wesnousky, 1985] are not directly applicable. Yet these methods provide the best data to reliably constrain recurrence intervals of strong earthquakes. The best available information is preserved in deformational features of surficial alluvial deposits, mainly induced by liquefaction. A number of workers have developed techniques to constrain past seismic events in time and space through the study of such features [Sims, 1973, 1975; Obermeier et al., 1985; Talwani and Cox, 1985]. Except for one trenching study near Reelfoot Lake [Russ 1979; 1982], the extensive sand blow, sand fissure and sunkland regions near the New Madrid zone have not been systematically investigated for evidence of pre-1811 earthquakes. Such a study would entail extensive mapping, trenching and dating of alluvial surface deposits. The overall objectives will be to constrain recurrence estimates for large earthquakes as obtained by frequency-magnitude statistical analysis [e.g., Johnston and Nava, 1985] and thereby greatly reduce the uncertainties that currently accompany central U.S. seismic hazard estimates. That such an objective is feasible has recently been demonstrated for the smaller Charleston, S.C. seismic zone [Obermeier, et al., 1985; Talwani and Cox, 1985].

(3) *Microzonation Research.* Beyond a regional seismic risk zonation, a city can best minimize earthquake damage through a detailed knowledge of local site response to strong ground vibration. This is particularly true for cities built on alluvial or uncon-

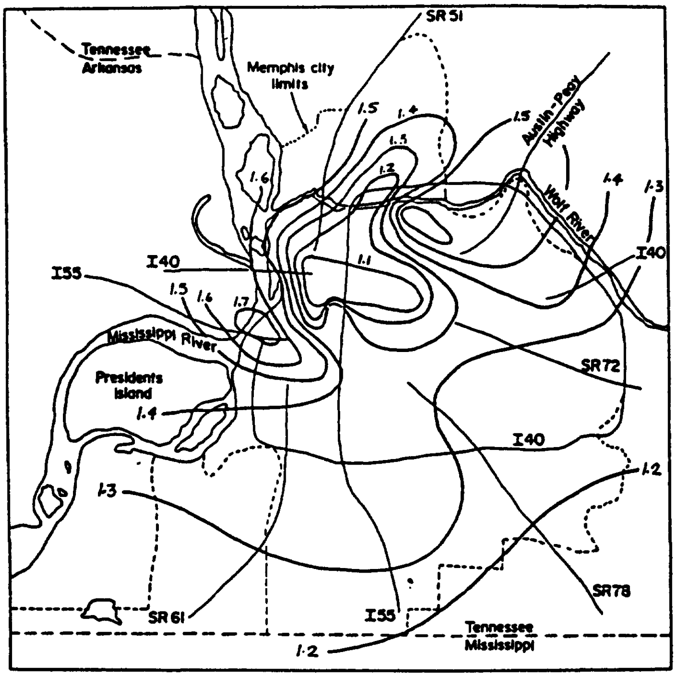
solidated soil foundations where soil column resonance and amplification can dominate the response spectrum. The devastating effects of the September, 1985 Mexico quake on Mexico City provided a tragic demonstration of this fact. There a subsurface clay layer amplified vibrations of about 2 seconds period, thereby strongly concentrating damage in buildings in the range of 5-20 stories.

I define microzonation as a detailed seismic hazard zonation according to local seismic response characteristics of foundation soils. This requires quantitative data assessment on the scale of a city block rather than the usual practice of using much larger regions (on the scale of state boundaries) for seismic zonation.

Initial work for the microzonation of Memphis was done in 1980 in a study sponsored by the U.S. Geological Survey [Sharma and Kovacs, 1980]. They found that in many areas of the County (Shelby) the acceleration from seismic waves would be increased by factors of 40-80% because of soil response (figure 2). They also mapped some areas susceptible to liquefaction.

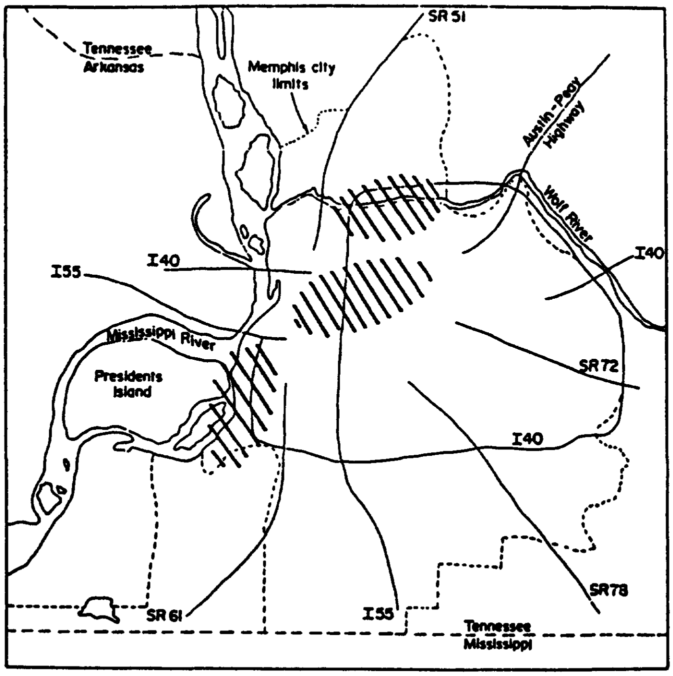
The USGS study, while an important first step, has barely begun the detailed work necessary for a comprehensive microzonation of Shelby County. The investigators did no new field work but relied on compilation of existing shallow drill data, much of which was proprietary and could not be accessed. The resolution of the maps in figure 2 is much coarser than is needed. Nevertheless, the study confirmed that large variations in effects of large earthquakes can be expected within the county and highlights the need for further detailed study.

The results of a Memphis microzonation study would have a utility considerably beyond the local Memphis area. The methodology that is developed can be applied to the numerous communities that are sited on the alluvial soil deposits of the Mississippi, Mis-



(A)

Contours indicate amplification factors for the assigned "bedrock" motion of 18% g.



(B) Shaded areas indicate zones where soils may be susceptible to liquefaction for earthquakes with Modified Mercalli Intensity greater than VII. (see discussion in text)

Figure 2. Ground amplification (A) and liquifaction susceptible zones (B) in Memphis, Tennessee due to hypothetical large New Madrid earthquake (Sharma and Kovacs, 1980).

souri, Wabash and Ohio River valleys. The ultimate objective would be to incorporate this detailed knowledge of soil foundation conditions into building codes and land use planning.

In this brief report I have provided just a few examples of the uses and application of earth sciences data to seismic hazard problems at national, regional and local scales. Although the data base is by no means perfect, it is at present sufficient to demonstrate the need, and to provide the necessary input for the aggressive planning and implementation of seismic mitigation and preparedness procedures in the central and eastern United States.

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COMMUNITY PREPAREDNESS PLANNING FOR EARTHQUAKES

by

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Earthquake hazards mitigation relies on the use of a combination of three strategies.

The first is earthquake hazard preparedness - which is the capability of an individual, the community, and the government to respond to an earthquake.

The second is land-use planning and regulation - which is planning and guiding the development and use of land in a community.

The third is the capability of buildings to withstand earthquakes - which generally requires the enactment and enforcement of appropriate building codes.

Scientific information is required for all the above strategies of earthquake hazard mitigation.

The potential for an earthquake disaster depends upon 3 factors. They are:

1) The magnitude of the earthquake.
   The larger the magnitude the greater the potential for generating severe levels of ground shaking and triggering other geologic hazards such as surface fault rupture and ground failure.

2) The location of the earthquake source relative to an urban area.
   The closer the source of energy release to an urban area the greater the potential for damage and loss of life.

3) The degree of earthquake preparedness within the urban area.
   The lower the level of preparedness the greater the potential for

catastrophic losses and social and economic disruption following an earthquake.

The earthquake that devastated the city of Tangshan, China, on July 28, 1976, is one example of an extreme earthquake disaster that could have been mitigated. Tangshan, an industrialized city of approximately one million people, was located in a seismic zone which, according to the Chinese building Code, did not require earthquake-resistant design. Therefore, this city of unreinforced brick buildings was almost totally unprepared for the physical effects of ground shaking which the magnitude 7.8 earthquake generated. The earthquake's epicenter was within the city and the causative fault ruptured within and beyond the borders of the city. The result was a very great disaster. Eighty-five percent of the city's buildings collapsed or were severely damaged and several hundred thousand people lost their lives. Industries in Tangshan were out of operation for long periods of time and it took more than 6 years for one-half of the city to be rebuilt.

The amount and type of damage which Tangshan sustained depended on the magnitude of the earthquake, its proximity to the epicentral region, and the amount and type of long-term earthquake preparedness and mitigation measures that the city had implemented. Tangshan and other communities have no control over the first 2 factors; therefore, to minimize the losses which will result from earthquakes, communities need to concentrate on implementing long-term earthquake preparedness and mitigation measures.

Communities have many policy options open to them. Because earthquakes occur infrequently, communities may implement these options over a period of many years. Each community will need to choose those earthquake preparedness and mitigation measures which best fit the needs and politics of its constituents. Below is a general list of preparedness and mitigation measures. Any combination of them will form a community's earthquake hazard policy.

1) Earthquake response plans, drills, and simulations at community, business, utility, school, family, and individual level.

2) Land-use planning including delineation of hazardous areas for comprehensive planning, land use regulations, and siting of public facilities.

3) Building codes and enforcement procedures for earthquake resistant design of new buildings.

4) Retrofit policy for public and private buildings and structures.

5) Insurance for individuals and businesses.

The implementation of the above measures will depend on the awareness and concern of individuals and leaders in the community. To increase hazard awareness and concern many communities will need to initiate earthquake education of the public including professionals, school children, and emergency responders.

Communities may also lack some of the important technical information necessary to implement all of the above mitigation measures. For example, site specific vulnerability studies are necessary for scenarios and most response plans. Maps identifying hazardous areas in a community are a prerequisite to land use regulations and prudent public facility siting. Maps delineating ground shaking hazards are necessary for building codes, and loss studies may be necessary for informed insurance decisions.

Lastly, a community will need to overcome political, informational, social, organizational, and economic barriers which many times will retard the implementation of earthquake hazard preparedness and mitigation policy. These are as follows:

1. <u>The earthquake problem is not a high priority for local officials or members of the community.</u>

   Atkisson and Petak (1982) and Nilson and Olsen (1981) have identified the low political salience of the earthquake threat as an important problem in the effective implementation of preparedness measures.

There are many more immediate issues that arise on a daily basis for political leaders and public officials. Given the long recurrence intervals for a major earthquake and the relatively short tenures of both elected officials and bureaucrats, the lack of interest in a relatively low probability risk is not surprising. Preliminary results from a study of Northeastern communities indicate that "in areas experiencing the reactivation of ancient faults, seismic safety is a very low priority issue for decision makers" (Dermengian et al., as cited in Nigg, 1981, p. 1071).

2. Necessary technical information is not definitive.

While technical information is seen as a necessary and elementary step in the development of seismic safety policies (Blair and Spangle, 1979; Berlin, 1980), it is also important to keep in mind that as the information is generated it needs to be interpreted for the public officials and professionals who must use it in making preparedness and mitigation decisions. Thus, two aspects of the technical information barrier must be considered: 1) the current information is not definitive and must be developed, and 2) once the information is refined, it must be translated for non-scientific users.

3. Adequate technical information by itself will not necessarily lead to appropriate action.

The weak link between information and action (or awareness of the hazard and appropriate action) has been well-documented (Saarinen, 1979; Palm, 1981). Numerous attempts have been made to model the relationship between attitudes and behavior and the role that information plays in this relationship. Because the relationship is still somewhat unclear it cannot be assumed that as more and more technical information becomes available, community leaders will base policy recommendations on such information. One researcher points out that the likelihood that exposure to new knowledge will influence behavior, assuming the audience has paid attention to and been persuaded by the information, is a function of "1) the degree to which behavior-relevant information is incorporated into the knowledge synthesis, 2) the degree to which the new knowledge is consistent with other attitudes and perceived as instrumental to the attainment of valued goals, and 3) the degree of institutional support . . ." (Weigel, 1979 as cited in Palm, 1981, p. 17).

4. Few advocates are organized around the issue of seismic safety.

   Atkisson and Petak (1982, p. 97) make the point that " . . . issues, problems and policy proposals which are not "owned" by responsible and attentive parties swiftly become undernourished and have a way of disappearing into the night."

5. The costs associated with policies for seismic safety are seen as prohibitive in an era of fiercely competing demands for limited public and private resources.

   Officials, and private sector representatives ask if the costs involved in the development of seismic safety programs are worth it, given that the risk to residents in their city is still somewhat undefined. Public officials particularly have set revenues from which they can develop programs; given that resources are limited and demands on them great, officials must ask if seismic safety programs represent the wisest use of these limited resources.

CONCLUSION

A community's success in implementing long-term earthquake hazards mitigation and preparedness policies will, in the end, depend on the dedication and skill of the local citizens and leaders who realize the extent of their community's risk from earthquake hazards and understand that they, along with State, regional and Federal leadership, have the capacity to reduce this risk.

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AN OVERVIEW OF IMPLEMENTING CUSEC'S GOALS

by

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INTRODUCTION

The stated objective of this paper is to address the purpose and goals of CUSEPP and to define what has transpired since the inception of CUSEPP to implement and achieve those goals.

Earthquake preparedness and mitigation efforts in the Central United States are young; many more years of time and dollars of support have been spent on similar efforts elsewhere in the United States. While the fledgling programs described here, in comparison, may seem less impressive than their counterparts, they should be analyzed with consideration for their newness and for the unique nature of the earthquake threat in the Central United States.

It is of great importance to define not only the goals of CUSEPP concerning earthquake preparedness and mitigation but the problems of implementing them. A discussion of those problems necessarily includes labeling what is needed to solve them in order to fulfill the intent of CUSEPP.

HISTORY

The Central United States Earthquake Preparedness Project was initiated in 1981 by the Federal Emergency Management Agency. The project followed Congress' passage in 1977 of the Earthquake Hazards Reduction Act and establishment of the National Earthquake Hazards Reduction Program. Congress instructed, in that program, that the federal government lead, coordinate and conduct earthquake research and hazard mitigation and disaster preparedness efforts.

Four federal agencies were given specific roles in the earthquake hazards reduction effort: the Federal Emergency Management Agency, the United States Geological Survey, the National Science Foundation, and the National Bureau of Standards. The Federal Emergency Management Agency, through CUSEPP, agreed to fund the Central United States Earthquake Consortium in 1984.

The Central United States Earthquake Consortium was established, in part, to fulfill goals of CUSEPP by promoting and supporting earthquake preparedness and mitigation efforts and by formulating plans and improving the administration of earthquake-related programs in the Central United States.

The CUSEC Board of Directors, which is comprised of emergency services directors from seven states--Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri and Tennessee, holds responsibility for the activities of the consortium. Thus, the groundwork was laid to plan regional earthquake preparedness and mitigation programs, to share technical and scientific information and other resources, and to cooperate in multistate efforts concerning earthquakes in the Central United States Seismic Zone.

THE CENTRAL UNITED STATES

The primary goal of CUSEC, in its earthquake preparedness and mitigation efforts, is to address the unique multistate nature of the earthquake threat in the Central United States. The Central United States Seismic Zone, unlike risk zones in California and Alaska, for example, encompasses seven states; in addition, it is apparent that a major earthquake on one of the faults located throughout the area could impact much of the eastern United States.

Studies completed within the last decade have more clearly defined the location and configuration of faults in the Central United States region and have explained why a major earthquake would have an inordinately wide effect. Scientists also have been able to discern patterns of occurrence in the regions numerous faults and have judged, based on that data, that the

Central United States is in great peril, despite the lack of visible faults or of recent major quakes.

With the establishment of seismographic data-collection networks, it was learned that unfelt ground shaking occurs in the region daily. Scientists projected, based on research, that earthquakes of about 4.5 on the Richter scale occur at the rate of approximately one in ten years and that earthquakes in the 6 to 7+ range occur about every 90 years. They reasoned that since it has been more than 100 years since the historical New Madrid earthquakes occurred in 1811-1812, strain energy has been building steadily, and the Central United States is increasingly vulnerable to a significant earthquake occurrence. Some estimate that, should the earthquake occur today, it could have a magnitude approaching 7.6 on the Richter scale.

Geological faults in the Central United States Seismic Zone apparently pose a frustrating problem for scientists in terms of location and measurement. Most are buried so deep beneath the Earth's surface that their exact configuration is difficult to define. In addition, neither can scientists easily see the effects of past earthquakes; they must rely at least partly on historical accounts and geological signs--such as sandblows--to determine where and when earthquakes might occur.

The uniqueness of earthquakes in the Central United States, then, is their distance--physically and psychologically. They are invisible, both to the eye and the memory. Scientists have made great strides in defining the threat of earthquakes. Residents of the region and the nation, however, have resisted accepting the idea of something they can neither view or remember. That the region is geographically large and culturally, socially and politically varied also has complicated earthquake preparedness and mitigation efforts.

The task, under which all earthquake-related efforts are included, of the Central United States Earthquake Consortium has been to overcome barriers that might hinder preparedness and mitigation efforts. It is likely that if a major earthquake occurs in one of the seven states most at risk, all will suffer. The guiding philosophies have been coordination and cooperation to overcome legal, political, geological and cultural barriers. A single political unit, for example, can more easily gain legislative support and enlist the help of existing entities--schools, businesses, government agencies and the like--than can a seven-state region. Resources are more easily shared during emergencies when the legalities of crossing state lines are not present.

Recognizing the complex nature of planning for earthquakes in the Central United States is necessary to understanding the work areas defined by CUSEC in its five-year plan. No prototype existed for the formulation of interstate emergency planning of a magnitude required by the present earthquake threat.

PREPAREDNESS AND MITIGATION EFFORTS

The Central United States Earthquake Consortium has defined five major areas of work:

* The development of the Interstate Earthquake Emergency Compact,
* The establishment of a Multistate Earthquake Data Management Resource Inventory,
* The refinement of multistate plans and the coordination of activities related to state earthquake disaster preparedness, response and recovery,
* The dissemination and sharing of earthquake-related information among disaster preparedness planners, educators and others, and
* The maintenance of the CUSEC office and the supportive coordination of operations.

The Interstate Compact will define the process whereby each of the states may share resources in the event of a multistate emergency. Goals are to establish an agreement among the states concerning short-term disaster assistance, which will likely involve sharing equipment, supplies, facilities and personnel in the fields of medicine, security, law enforcement and firefighting, and industries with appropriate resources. A second goal of the compact is to provide some assurance of protection for those who render professional services during a disaster in states other than their own.

The Multistate Earthquake Data Management Resource Inventory will be a comprehensive, exhaustive listing of all resources in the seven-state region that might be needed in an earthquake disaster. Each of the CUSEC-member states will maintain a bank of standardized data to be used in the inventory. The information will be accessible at all times to all seven states.

The Response and Recovery Planning Initiatives will include integrating each of the seven states' emergency management plans into a common response strategy. Central to the plan is establishing a communications system through which states can immediately receive information and use the resource inventory and digitized mapping systems. A series of exercises will be held to test and evaluate the integrated emergency management plan.

Preparedness and mitigation planning inherently affects every person in the seven-state region. Basic to citizens protecting themselves against the potential disaster of a major earthquake is knowledge. The Public Affairs Awareness Program involves the government and private sector and includes the development of educational materials; participation in earthquake-related government, professional and public meetings; establishment of an earthquake information resource library; and the involvement of media in public information and educational goals.

Of particular importance concerning informational efforts is the need to provide an informational exchange forum for those individuals who will be involved in preparedness, response and recovery planning as well as those involved in mitigation planning.

To address this need, CUSEC has established parallel discipline committees and special issue committees. Convened sessions of the committees are opportunities for information exchange by individuals from selected professional disciplines (parallel discipline committees) and by individuals primarily from government entities with similar responsibilities in the risk states (special issue committees).

Examples of parallel disciplines committees are medical, geology and seismic, and mitigation and engineering. Special issue committees include education, public information and legal issues.

Efforts and activities by CUSEC as supported by FEMA have brought an enhanced earthquake risk awareness level to the residents of the CUSEC area. Also, the operational networks whether structured and formal or subtle and informal have brought opportunities to the earthquake planners of the risk area.

During the second year of CUSEC, the current year, it is expected significant progress will be realized.

THE 19 SEPTEMBER 1985 MEXICO EARTHQUAKE: TECHNICAL PROBLEMS

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ABSTRACT

The September 19, 1985, Mexico earthquake reminded scientists and engineers of the importance of considering soil amplification effects in earthquake-resistant design. The Mexico earthquake illustrated the "worst case"--the ground response and the building response occurring at approximately the same period, 2 seconds. This resonance phenomenon was predictable on the basis of similar experiences in past earthquakes. A number of areas in the United States also exhibit significant predictable soil amplification effects. Special steps are needed in these areas to mitigate the potential damage and losses that could occur in future earthquakes.

INTRODUCTION

On Thursday morning, September 19, 1985, at 7:18 a.m., a great earthquake having a magnitude (M_s) of 8.1 occurred at a depth of about 11 miles in the Mexico trench subduction zone along the boundary of the Cocos and North American tectonic plates. The epicenter was located near the town of Lazaro Cardenas on the border between the states of Michoacan and Guerrero. Parts of Mexico City, the World's most populated urban center with more than 18 million people and more than 1 million engineered structures, experienced severe damage, in spite of the fact that Mexico City was 250 miles from the epicenter.

The earthquake was caused by a 125 mile-long rupture along the boundary of the Cocos and the North American tectonic plates. The Cocos tectonic plate is slowly being subducted at the rate of about 3 inches per year underneath the North American plate. The zone of subduction stretches for more than 1,000 miles along the Pacific coast of Central America. The Mexico trench

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subduction zone is well known. It has ruptured in the past and has been the source of large earthquakes that have shaken Mexico City as well as the central and southern parts of Mexico. Similarly as in 1985, parts of Mexico City experienced severe damage in 1957 and 1979 from earthquakes in the subduction zone. A seismic gap (a segment of the interface between the Cocos and North American tectonic plates that has not ruptured in past large earthquakes, but which has the potential of producing a future large to great earthquake filling the gap) was recognized in the Michoacan-Guerrero area by McNally in 1981. She made a general forecast of a future earthquake. The 19 September 1985 earthquake is generally considered to have filled a portion of the Michoacan-Guerrero seismic gap.

EFFECTS OF THE EARTHQUAKE

The 1985 Mexico earthquake was noteworthy for several reasons. The effects of the earthquake are synthesized from several reports (National Academy of Sciences, 1985; Beck and Hall, 1986; and Rosenblueth, 1986) and are summarized below:

1) An estimated 10,000 people were killed in the earthquake and many more people were injured. Economic losses are estimated to have reached $5 to $10 billion. One quarter million people were left homeless.

2) Both the epicentral region, located near Lazaro Cardenas, and parts of Mexico City were assigned an intensity of IX on the Modified Mercalli Intensity scale, an unusual phenomenon. No other historic earthquake anywhere in the world has had locations 250 miles from the epicenter that were assigned an intensity of IX.

3) The earthquake caused partial to total collapse of about 300 five to twenty story buildings in Mexico City, located some 250 miles from the epicenter. Search and rescue operations were an important element of the initial response to the earthquake.

4) Hospitals were severely affected by the earthquake. Six buildings collapsed at the Mexico General Hospital. About 400 doctors, nurses, and patients were trapped in the ruins of the Jurarez Hospital

5) Government buildings as a group were severely damaged in the earthquake. The specific explanation of the high degree of damage to this group of buildings is not yet known.

6) Because of prior planning by American and Mexican scientists and engineers, a number of strong motion accelerographs were operating at the time of the earthquake in both the epicentral region and in Mexico City.

7) The instruments in the epicentral region registered a peak horizontal ground acceleration of 0.18 g as did the instruments in Mexico City that were underlain by soft unconsolidated deposits of an old lake bed. Other instruments in Mexico City underlain by stiffer rock-like material registered a peak horizontal ground acceleration of 0.04 g, or less.

8) The duration of shaking in Mexico City was long, on the order of 3 minutes.

9) In spite of the "bad news" that several hundred buildings in Mexico City collapsed and several thousand more had to be demolished or strengthened, the "good news" is that the severely damaged buildings represent <u>less</u> than 1 percent of the more than 1 million engineered structures in Mexico City. In terms of the philosophy of a building code--"to resist major earthquakes without collapse, but with some structural and nonstructural damage"--the outcome from the point of view of the building code was reasonable, <u>except</u> in the lake bed zone underlying Mexico City. In that zone, the code was inadequate to resist the large forces.

Rosenblueth (1986) lists seven factors (besides the severe shaking) that contributed to the overall structural damage. They are:

1) Pronounced asymmetry of buildings.
2) Corner locations.
3) Weak (soft) upper and middle stories.
4) Pounding of adjacent buildings.
5) Poor foundation.
6) Excessive mass.
7) Prior damage in past earthquakes.

WHAT CAUSED THE SEVERE DAMAGE IN PARTS OF MEXICO CITY?

Much of the extraordinary degree of localized damage in the lake bed zone of Mexico City was predictable. It was caused by a double resonance phenomenon involving the response of the underlying lake bed and the response of the five to twenty story buildings to the amplified 2 second period ground shaking (Rosenblueth, 1986). Worldwide experience in destructive earthquakes (e.g., 1957, 1962, and 1985 Mexico; 1967 Caracas, Venezuela; 1970 Gediz, Turkey) has shown that the kind of ground that a building is founded on affects the amplitude, spectral composition, and duration of the ground shaking input into the building and the type and degree of damage it receives. Scientists and engineers have recognized and documented in the technical literature of earthquake engineering and engineering seismology since the 1800's that lateral and vertical changes in the physical properties of the soil-rock columns underlying a site modify the amplitude level, the spectral composition, and the duration of the ground motion recorded at the surface in a predictable manner (MacMurdo, 1824; Seed and Idriss, 1969; Seed and others, 1972; Tezcan and others, 1972; Hays, 1980; Singh, 1985). The soil-rock column underlying a particular site acts like a filter, causing the amplitude of the surface ground motion to be increased (amplified) in a narrow range of periods (or frequencies) and decreased in other period ranges. The amplitude of the enhanced ground motion is a function of the contrast in physical properties (shear-wave velocity, density, material damping) between the soil and the underlying rock, the geometry of the soil rock interface, and the surface and subsurface topography. The dominant period of the enhanced ground motion is a function of the thickness, geometry, shear modulus, and shear-wave velocity of the soil column. Because soil behaves in a strain-dependent manner, the level of dynamic shear strain induced in the soil is the most important factor, causing the amplitude to decrease and the period to increase as the level of strain increases.

A soil column, like a building, has a natural period of vibration (Figure 1). the characteristic period T_s of a soil column is given by the relation

$$T_s = \frac{4H}{V_s} \qquad (1)$$

where H is the thickness of the soil column and is V_s the average shear-wave velocity of the soil measured under conditions of low strain. The period for a building T_b is given approximately by the relation

$$T_b = \frac{N}{10} \qquad (2)$$

where N is the number of stories.

Although many areas of technical controversy exist, studies of ground response, building response and damage from past earthquakes have clearly shown two facts:

1) Amplification of the ground motion by a factor of 5 or more in a narrow period band centered around the characteristic period of the soil column is caused by a contract in the shear-wave velocity and the thickness of the soil-rock columns, and is essentially independent of strain up to levels of about 0.1 percent (Hays, 1980; Toki and Cherry, 1972).

2) The greatest levels of shaking in a building occur when the vibration of the building coincides with the natural period of vibration of the column of soil overlying rock-like material.

Rock-like material is defined as any material having a shear-wave velocity of 760 m/sec or greater; whereas, soil has much lower shear-wave velocities, typically in the order of 100-500 m/sec.

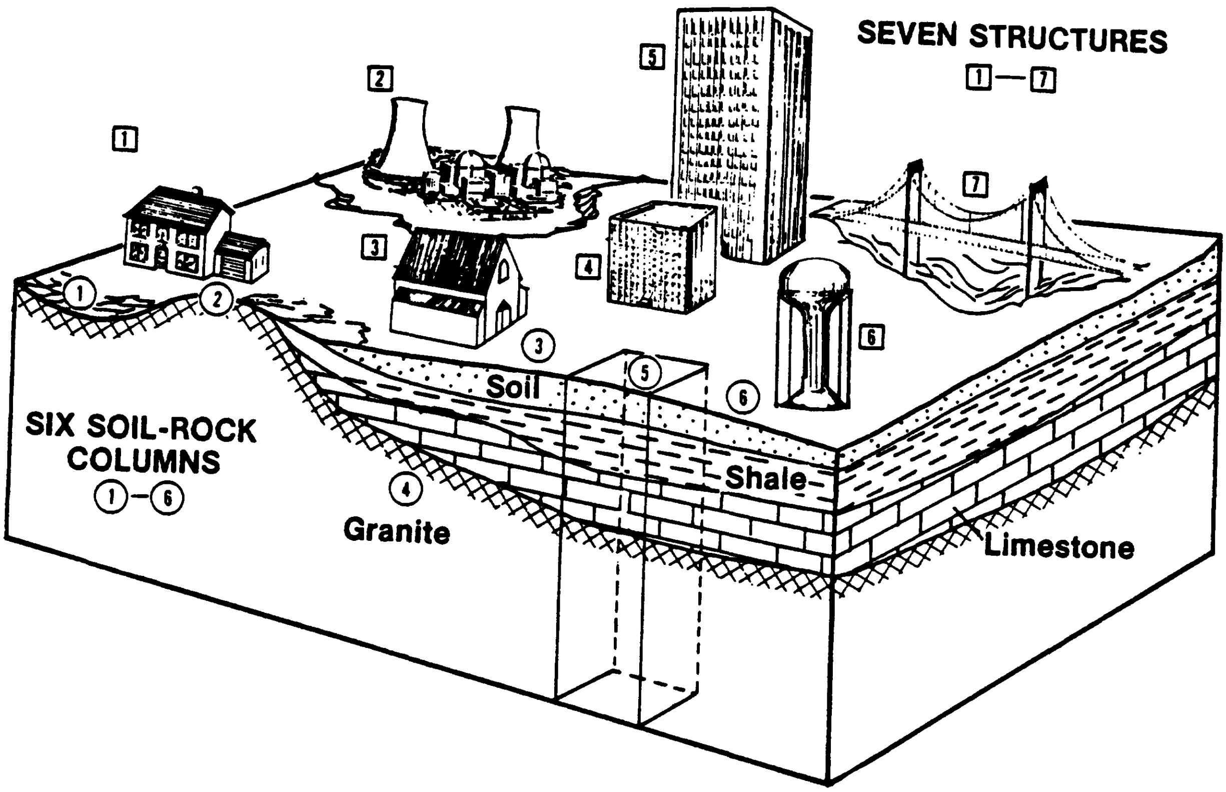

Figure 1.--Schematic illustration of six soil-rock columns and seven types of structures. Each soil-rock column and each structure have a fundamental nature period of vibration. If the dominant period of the earthquake-induced ground response coincides with the dominant period of the structural response, severe damage and collapse can occur.

Understanding the physics of local ground response requires consideration of the ground-motion time histories. Typical horizontal acceleration, velocity and displacement time histories display the superposition in time of elastic waves that have traveled a wide variety of paths between the earthquake source and the recording site (Figure 2). It is impossible to delineate all of the travel paths involved because one would need to know the details of the geology between the source and the receiver to a depth of perhaps the Mohorovicic discontinuity (i.e., in the order of 30 km). Although such detailed information is usually not available, both theoretical considerations and experience indicate that the seismogram is composed of body and surface waves. The body waves are the familiar compressional (P) and shear (SV and SH) waves which travel from the source to the recording site along paths which extend deep into the Earth's crust. Because of the nature of these travel paths, the energy associated with these wave types is vertically incident on the site geology from below. These waves mainly cause short-period (i.e., periods less than 1 second, (high frequencies) which are efficient in causing low-rise buildings to vibrate. The surface waves (Love and Rayleigh), on the other hand, propagate through channels or wave guides which are bounded above by the surface of the Earth. Thus, they traverse the site geology laterally rather than being incident from below. They mainly cause long-period (low-frequency) vibrations which are efficient in causing high-rise buildings to vibrate. Because the body and surface wave types travel at different velocities, they are separated in time on seismograms recorded some distance from the epicenter. The separation of the seismogram into contributions due to the arrival of body and surface-wave types means that both types of elastic waves must be examined in order to evaluate local ground response effects in a comprehensive manner.

Figure 3 illustrates the time histories of horizontal acceleration, velocity, and displacement observed in Mexico City from the September 19, 1985, Mexico earthquake. The striking feature of these strong motion time histories is the dominant 2-second period of the accelerogram which was recorded 250 miles kilometers from the epicenter of the magnitude (Ms) 8.1 earthquake. This phenomenon was caused by the filtering effect of a 50-meter thick soil column

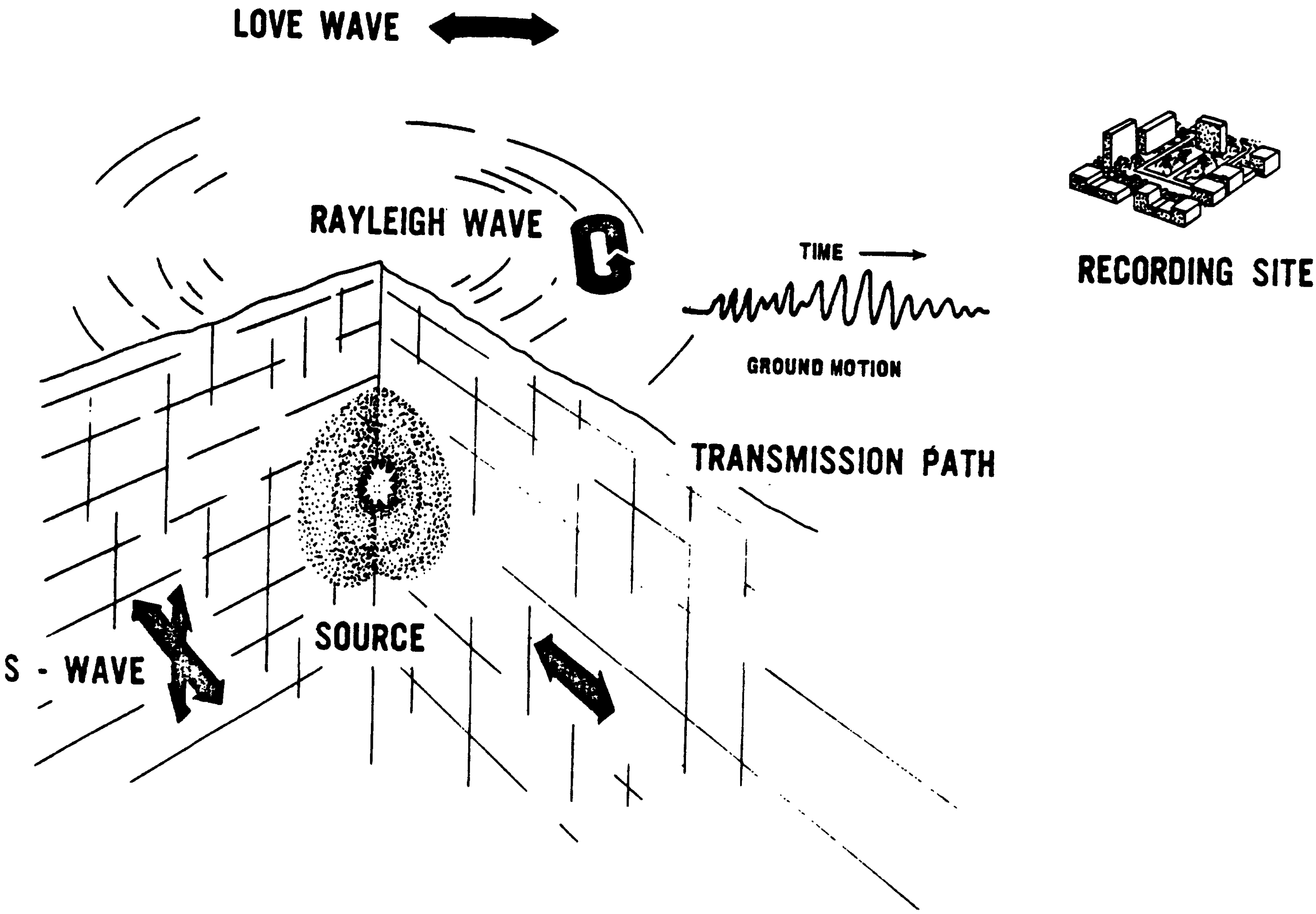

Figure 2.--Schematic illustration of the elements that contribute to the amplitude and frequency composition of earthquake ground motion recorded at a site. The local geology underlying the recording site acts like a filter and can significantly amplify certain frequencies of the ground motion input to a building. The building also acts like a filter and can amplify the input ground motion even more.

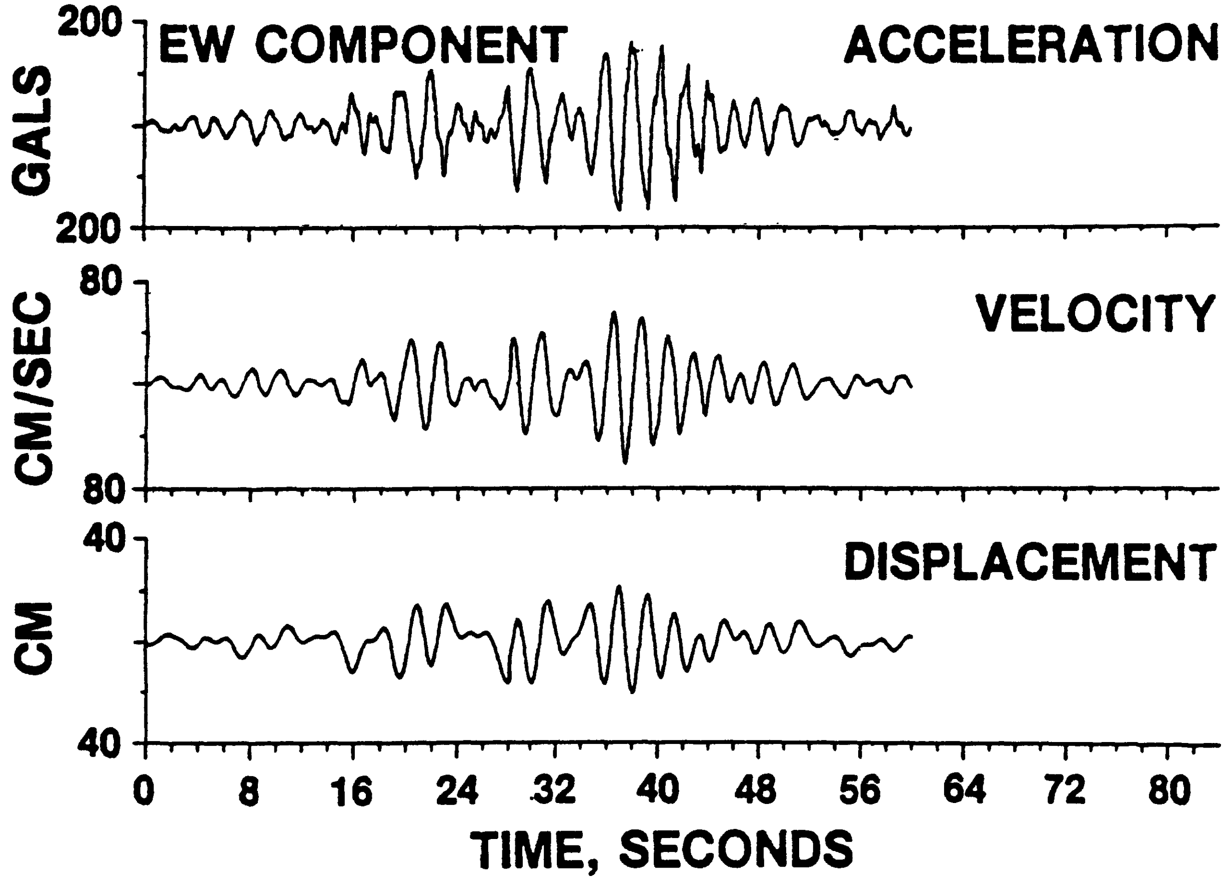

Figure 3.--Accelerogram (top) recorded at a free field location on the surface of the 50-meter thick lake beds forming the foundation in parts of Mexico City. The epicenter of the September 19, 1985, Mexico earthquake was located some 400 km to the west. The strong 2 second period energy in the accelerogram and the velocity (middle) and displacement (bottom) time histories derived from it are a consequence of the filtering effect of the lake beds which amplified the ground motion, (relative to adjacent sites underlain by firmer rock-like materials) about a factor of 5. The coincidence of the dominant period of ground shaking (2 seconds) with the fundamental period of vibration of tall buildings contributed to their collapse. These records were provided by the Universidad Nacional Autonoma de Mexico.

representing deposits by a former lake bed that now underlies parts of urbanized Mexico City. The shear wave velocity of these deposits is about 100 m/sec; therefore, their characteristic period is 2 seconds--the approximate natural period of a 20-story building (Zeevaert, 1964). When one allows for the normal range of variation in both the shear-wave velocity and the thickness of the soil column, the characteristic site periods in Mexico City can easily vary from 0.5 to 2 seconds and coincide with the range of natural periods of vibration of typical 5- to 20-story buildings, the classes of buildings in Mexico City that were most severely damaged.

Where in the United States have Similar Soil Amplification Effects Occurred?

A number of researchers have published information about local ground response in different parts of the United States. The areas having potential for site amplification in future earthquakes include:

1) San Francisco region--The San Francisco Bay mud causes the most significant effect. The short periods of ground motion are amplified by as much as factor of 10 (Borcherdt, 1975).

2) Los Angeles region--The varying thicknesses of alluvium cause short-period (0.2-0.5 second), intermediate-period (0.5-3.3 seconds), and long-period (3.3-10 seconds) amplification, depending on the location in the Los Angeles basin. The mean amplification factor varies from 2 to 5 (Rogers and others, 1985)

3) Nevada--A classic example of body wave amplification was observed in Tonopah, Nevada, where a site underlain by fill experienced short-period amplification of a factor of 7 at a period of 0.14 seconds relative to an adjacent site underlain by rock (Murphy, and others, 1971) Hays, 1978). The classic example of surface wave amplification was observed in Las Vegas where the varying thicknesses of alluvium amplify the long-period (2-3 second) surface waves by a factor of about 10 with the greatest response occurring at sites underlain by thick, water saturated deposits of clay and silt (Murphy and Hewlett, 1975).

4) Wasatch Front, Utah--Salt Lake City, Ogden, and Provo, the principal cites along the 210 mile-long Wasatch fault, are founded on several different types of soil deposits related to the filling of the Great Salt Lake basin. These deposits amplify the ground motion in the period band 0.2-0.7 second by as much as a factor of 10 (Hays, 1986).

5) Parts of the Mississippi Valley--The July 1980 Kentucky earthquake caused damage in some locales that was explained in terms of site amplifications phenomena. Many locations having thin, stiff soil columns as well as thick, soft soil columns exist in the Mississippi Valley area.

6) Boston--The Boston area has zones of landfill and poor ground that could potentially amplify earthquake ground motion.

CONCLUSIONS

Lessons for other parts of the United States--Many important lessons can be extracted from the experience of the 1985 Mexico earthquake. Three general lessons are applicable to many parts of the United States and are summarized below:

1) Buildings located on soil deposits are most likely to experience severe damage if the dominant vibration periods of the ground and building coincide. Urban development should avoid this condition if possible, or make certain that proper engineering is performed if it cannot be avoided.

2) Building codes must explicitedly address the problem of double resonance between the ground and building. Earthquake-resistant design criteria must be stringent enough to account for the potential amplification of ground motion by the local soil rock columns. Design considerations must extend to stairways and other nonstructural elements; otherwise, search and rescue efforts are adversely is affected.

3) Emergency response plans must include consideration of search and rescue operations of the type experienced in 1985 in Mexico City--a worst case scenario.

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BUILDING RESEARCH NEEDS FOR EARTHQUAKE HAZARDS MITIGATION MEASURES IN THE CENTRAL USA

by

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INTRODUCTION

Various estimates of the potential life loss and economic loss from a repeat of the New Madrid earthquake of 1811 or 1812 have been made. These estimates suggest that tens of thousands of lives and billions of dollars could be lost in one such earthquake in southern Missouri. On September 19, 1985 an earthquake off the western coast of Mexico resulted in about 20,000 lives lost and over five billion dollars in damage. Most of these losses occurred in Mexico City about 250 miles from the earthquake epicenter. Mexico City has modern earthquake resistant design building codes and most of these modern buildings did not collapse. However, most of the fatalities were in pre-modern code buildings of construction similar to that existing in the Central USA today. Thus from this recent experience in Mexico previous estimates of potential life loss from a reoccurrence of the New Madrid earthquake may be too low. In order to accurately assess vulnerability for life loss it is necessary to establish a means to reliably ascertain the earthquake response structural capability of our existing buildings and bridges to resist life threatening collapse. A logical first goal of a hazard mitigation program would be an assessment of the life hazard vulnerability. At the present time little is known of the response behavior of existing buildings and bridges as they approach failure due to earthquake loading. Specifically the margins between earthquake ground motions which cause damage, severe damage, and life threatening collapse are not known.

The vulnerable man-made structures must be demolished or made life hazard safe through implementation of appropriate remedial actions. The choice between demolishing a building or increasing its life safety earthquake resistance is an economical and political decision which should be made on the basis of the best information available. As a first step research is needed to develop experimentally and analytically verified techniques for repair, strengthening and retrofitting existing Central USA hazardous buildings and bridges. To reduce life loss vulnerabilities, techniques for economical repair, strengthening and retrofitting appropriate for these classes of existing hazardous buildings need to be demonstrated and implemented. A second goal of the earthquake hazard mitigation program should be to determine the margin between damage and collapse for the significant classes of hazardous existing midwestern buildings and bridges in order to establish techniques for the identification of the most vulnerable structures for early remedial action. The information and techniques gained from this effort could have applicability beyond the Central USA.

Implementation of vulnerability assessment and imposing remedial measures will require a long term effort to reduce the existing life hazards. A third goal of the program is the initiation of appropriate actions by professional and elected officials of vulnerable cities. Technical and procedural assistance by knowlegeable individuals from professional and research organizations and governmental agencies should be offered to efficiently implement the necessary remedial actions.

A possible fourth goal of an earthquake hazards mitigation program which would have significant long term benefits for new and existing construction is the creation of innovative building systems for superior earthquake resistance. Because creative concepts cannot be solicited on demand, a portion of each year's funds should be allocated for individually generated creative concepts. An open competition for "earthquake mitigation creativity funds" could be announced nationally; requesting proposals from any USA citizen or permanent resident participant; and selecting the winning ideas by an appointed selection committee.

RESEARCH NEEDS

The four major needs identified in the preceding were (1) the assessment of the life hazard vulnerability of midwestern cities caused by earthquake damage potential of their man-made structures, (2) the identification and verification of techniques to determine the margin of safety between the earthquake level which causes structural damage and the earthquake level which causes life threatening collapse, (3) the implementation of remedial measures to reduce the life hazard potential from earthquakes in these cities, and (4) the development of innovative construction systems for enhanced earthquake resistance.

1. Structural Capability of Existing Buildings.

In order to establish the earthquake resistant structural capabilities of existing buildings a coordinated full-size field experimental, analytical, and laboratory experimental research effort is needed. Full-size field experimental data from existing buildings will provide information regarding three-dimensional structural interaction as various elements in the structure are damaged and will provide a means to establish the levels of earthquake excitation necessary to cause various levels of damage and life threatening collapse. To accomplish this it is necessary to test existing buildings or portions thereof to destruction. This costly, but necessary, experimental program needs to be closely coupled with a nonlinear analytical program development to assist with selection of test parameters and to investigate other existing buildings of similar construction but different geometrical configurations in order to eliminate the need for full-scale destructive testing of all building variations.

One possible approach would be as follows: During the first year the classes of most life threatening construction in the Central USA would be identified utilizing current hazard assessment techniques [1] and studies like Nowak [2] prepared for commercial buildings in Memphis. This investigation will result in a list of hazards potential which considers occupancy type, construction type and construction year. The next step would be a preliminary experimental evaluation of existing building seismic capabilities through full-size building subassemblage tests. These laboratory experiments should be conducted under the supervision of experienced researchers. From the 1985 Mexico City experience it is anticipated that reinforced concrete frames with masonry infill walls or light steel, concrete and masonry composite buildings should be the first to be tested. The actual materials for the specimens and their configurations depend upon the hazardous building identification results.

The priority list of classes of life threatening hazardous buildings will provide a shopping list of potential test buildings. It will be desireable to identify target buildings for full scale destructive tests in the Memphis/St. Louis area because they will be the most similar in construction technique and deterioration effects as the general population of hazardous buildings to be evaluated. However, similar buildings in other midwestern cities, such as Chicago, Cleveland, Detroit, or Toledo, can provide a reservoir of potential test buildings.

The results of this experimental and analytical coordinated program can provide input to a vulnerability assessment for a broader range of existing buildings by using probabilistic methods and system reliability techniques. Thus the results of this effort can provide the basis for reliable life safety vulnerability assessments for any building upon demand.

2. Techniques for Repair, Strengthening and Retrofit.

A number of techniques have been used in various parts of the USA and other seismically active countries of the world to strengthen existing structures for greater seismic safety. Some of these techniques have been implemented and subsequently subjected to significant earthquake ground motion such as in Mexico City. But in general, techniques commonly used in the USA have been developed on an analytical basis and implemented without experimental verification of the actual behavior of the modified system.

To provide the necessary data to reliably implement various techniques for the repair and strengthening of buildings a series of prototype existing structures will be repaired and tested to damage and failure levels. Prior to full-scale prototype testing pilot tests of these techniques with three directional loading should be made to provide assurance that the proposed technique is satisfactory. As discussed above the most effective approach would be to utilize the current test building specimen for this purpose. Because the prestrengthening characteristics would have been well established the contributions of the modifications can be clearly identified. Earlier research efforts provide the basis for elemental member behavior [3,4,5,6,7,8,9,10] in the design of various strengthening techniques, such as steel bracing members, column strengthening, infill precast walls, and supplemental damping. Experiences of design engineers in evaluating proposed retrofit measures should also be utilized.

3. Implementation of Vulnerability Assessment Procedures and Initiation of Remedial Measures

The results available from efforts 1 and 2 above will have limited impact upon the life hazard vulnerability in the Central USA unless building officials, building owners, public servants, and elected officials decide that action must be taken. Thus, the results of the vulnerability studies must be expanded to cover each of the major cities in the region. In each of these cities the characteristics of the building inventory and the classes of building structural systems must be coupled with the seismic intensity site characteristics to develop a rational basis for the local life hazard assessment. The procedures developed earlier can be used for this purpose.

By working closely with the existing local, state, and federal organizations and agencies reponsible for the safety of their citizens in demonstrating that remedial measures are needed and are cost effective, elected official support of these remedial actions should be possible.

4. Creation of Innovative Building Systems for Superior Earthquake Resistance.

A "creativity" fund should be established to provide seed funds for the development of innovative methods to provide increased earthquake resistance. This could be for either existing or new construction and competition for these funds would be open to any individual or organization whose members are USA citizens or permanent residents. While this should not be a major activity , creative ideas often develop from trying to solve similar problems in a traditional manner. These funds are to encourage creative thinking while working on current problems. It would be expected that these creativity projects are of limited scope and budget and that the individual would "cost share" with his personal time.

CONCLUSIONS

It is known that the largest earthquakes in the continental United States occurred in 1811 and 1812 in southeastern Missouri (commonly referred to as the New Madrid earthquakes). A reoccurrence of an earthquake in that region of that size can cause massive destruction of man-made structures and a disasterous loss of human life. The major cities of Memphis and St. Louis will be the most severely effected, but life loss and damage will occur over a much wider area. Unless something is done to protect these people, our country will have a national tragedy beyond the worst fears of most of our leaders.

The vulnerability of our buildings and their associated earthquake risk exposure must be assessed. The United States Geological Survey, the Nuclear Regulatory Commission, the National Science Foundation, and the Electric Power Research Institute have made extensive studies of the earthquake hazards in the eastern United States. The results of these studies provide an excellent base from which site risk exposure can be established. The missing element is an accurate assessment of the earthquake resistant capabilities of existing man-made structures.

The vulnerable man-made structures must be demolished or made less vulnerable through implementation of appropriate remedial actions. The choice between demolishing a building or increasing its earthquake resistance is an economical and political decision which should be made on the basis of the best information available. At the present time little is known of the behavior of existing buildings and bridges as they approach failure. More specifically the margin between damage, severe damage, and life threatening collapse is not known.

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NEEDS FOR DEVELOPMENT AND ADOPTION OF EARTHQUAKE MITIGATION MEASURES RELATED TO LAND-USE AND BUILDING PRACTICES

by

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Introduction

Earthquake hazards mitigation measures include many possible strategies. The focus for seeking information needed for mitigation that will impact the issues of land-use and building practices (application of codes) requires that we:

1. Identify causes of anticipated damage,
2. Estimate expected damage,
3. Evaluate the severity of the damage, and
4. Develop strategies for mitigation.

In the Central United States efforts are practically in their beginning stages with respect to adoption of planned earthquake mitigation measures. Radical changes in operating procedures for land-use planning and for construction practices should be carefully considered. Differences in requirements for adopting mitigation measures in comparison with the California experience must be recognized. Time is required to correct land-use planning directions and construction practices that have become based on tradition and which may have placed high vulnerability structures with great loss potential in the most hazardous situations during earthquake. Therefore, in the meantime, other mitigation measures such as response planning and evacuation will be needed. However, planning for appropriate building safety related to land-use policy and code implementation in coordination with earthquake safety conscious construction practice <u>must</u> be started.

IDENTIFICATION OF CAUSES AND EXPECTED DAMAGE

Cities along the upper Mississippi Embayment, specifically along the Mississippi and Ohio Rivers are underlain by silt, clay and sand with high water content. For example, the entire City of Louisville, Kentucky is underlain by an aquifer ranging from 50 to 100 feet thick containing several billion gallons of water (1). Little or no data has been accumulated for the purpose of evaluating ground motion characteristics of soil deposits along the Ohio River (2, pgs. 34,166). In these regions where slopes with soil moisture is high, the possibility of landslides should be considered. Also, much of the ground underlying cities along the Ohio River should be expected to be susceptible to possible liquifaction as a result of earthquake ground movement.

Low attenuation of ground waves (2, pg. 7) combined with greater depth of deposits and taller structures may produce serious hazards at distant cities along river banks. The 1985 Mexico earthquakes gave ample evidence of the realities of this result (Mexico City was 250 miles from the epicenter). Cities such as Louisville, Cincinnati and St. Louis may be at risk due to earthquake even considering their distances from the expected source of ground arrays. The evaluation of the levels of risk must be determined by analysis of expected ground motion data.

Liquifaction caused by peak ground acceleration levels and duration of motion (3) in deposits along the Ohio and Mississippi Rivers should be expected to produce ground instability or failure under structures. The City of Niigata, Japan was severely damaged in 1964 by an earthquake with magnitude 7 and epicenter approximately 30-miles away. The city was constructed on an alluvial river plain with high water table. Ground accelerations with peak velocities about 0.15 g and duration of strong motion about 20-seconds occurred. Building construction in the city consisted of a large number of earthquake resistant buildings yet economic loss was about one billion dollars produced mostly from soil failure (4, p. 1). Ground failures due to liquifaction during the Alaskan earthquake of 1964 caused greater than one-half of the total economic loss (2, p. 41). Whereas, during the Mexico earthquakes of 1985, duration of ground motion resulting in large ground displacement was the major cause of damage. Either situation may result in the Central United States, large relative displacement or ground failure due to liquifaction. Longer periods at greater distances from the epicenter will cause problems with taller structures or with lifelines. Damage resulting from these causes is to be avoided. The effects of land slides (5) must be considered in the category of ground failure.

STRATEGIES FOR MITIGATION

Data:

(a) The significant damage possible from soil failure requires a reasonable estimation of expected ground acceleration levels. Data required includes use of standard penetration tests (blow counts) in combination with expected accelerations to determine liquifaction potential (3). Also, determination of probable soil failure accompanying landslide will be needed. Expected values of groundwave attenuation and of amplifications in ground motion or increased period of vibration due to depth of soil deposits should be analyzed in cities where damage will be great. Collection and evaluation of these data will enable consideration of choices for mitigation of earthquake hazard conditions not presently considered in many building codes in the Central United States.

(b) Available ground motion data for computing estimated ground spectra for design and existing intensity risk maps should be applied in localities within cities with possible significant damage and loss, or in regions of expected intensity IX or higher. Presently, building codes in the Central United States are outdated with respect to earthquake safety provisions. Earnest attempts are needed to encourage adoption of the NEHRP provisions (7) as early as possible. In the meantime, available ground acceleration data must be used for estimating liquifaction potential and ground failure. Determination of probable soil failure at certain localities will help to advise land-use planners and building officials of risks leading to potential loss.

(c) Ground motion data and information leading to computation of the potential for ground failure are available from existing research sources. Additional liquifaction analysis data from soil penetration tests may be obtained from consulting firms and soil testing firms. Procedures for acquiring existing data of soil penetration tests from local sources are subject to proprietary limitations.

STRATEGY IMPLEMENTATION:

(a) Localities within a city at which the potential for excessive ground movement or of ground failure exists should be analyzed in relation to the risk of loss. Guidelines are needed because these conditions may not receive proper attention in routine land development and building construction practices. Heavily populated areas and developed areas of major economic value to the community should be evaluated based on probability of potential loss. Within each locality in a city analysis of structures of usual construction is needed to evaluate probable loss. Data produced should consider several earthquake energy levels capable of resulting in building collapse. This information should be applied during the planning stages before design and construction of the building. The purpose is to provide data to land-use planners and building officials about the potential risk due to earthquake hazard in critical areas of the city. Localities that exhibit no potential risk due to ground failure or excessive ground motion will be subject to the usual practice for planning and building construction approvals. Final site selection and structural design of a specific building is the responsibility of the owner/developer. The information to be used for planning land-use should provide approximate risk data for ground failure and excessive ground motion if not consistent with the existing building code. Excessive ground motion requires the consideration of building types that may be exposed to several possible earthquake magnitude levels over a broad area of the city. Therefore, this information is used only for the purpose of providing information about the potential risk and to alert officials, owners and developers of the need to consider this risk.

(b) Land-use planning is a practical measure to achieve earthquake mitigation. The process is immediately effective when applied. That is, the effects of earthquake safety derived from land-use planning are realized at each site that receives seismic safety consideration. Land-use planning should be used to mitigate effects of ground failure or to provide for limitations of the building code. Land-use planning may be achieved through adoption of several options:

1) Zone limitation represents avoidance of possible hazardous conditions through suggested appropriate planning procedures. This option is used to restrict construction. Use of available data for earthquake safety obtained by procedures described above will provide land-use planners with quantitative information about the risks involved. Therefore, planners and building officials may be assisted in considering reasonable building restrictions based on potential for ground failure. Restrictions may be removed or reduced based upon further site evaluation and adequate design of the specific building performed by the owner/developer. This option is applied in areas that are considered to result in loss due to earthquake if the applicable building code only were applied in the development of a site within the locality. One possible solution taken by an owner/developer may be to avoid construction at the site.

2) Adequate building strength may be provided based on further investigation by the owner/developer to insure adequate safety against loss. The information used by planners and building officials to suggest needed acceptable safety levels to avoid potential risk of loss is based upon the conditions of ground failure or excessive ground movement. This information should only be applied to guard against the possibility of loss. Actions taken by the owner/developer may include appropriate foundation design to reduce the potential of ground failure. Such actions include lowering the water table through trenching, gravel column uses, compaction, etc. Selection of appropriate building types and adequate strengths are viable options. Consideration of appropriate strategies should be made by the owner/developer.

3) Fire safety is concerned with specifying zones within which certain high risk regions may be defined for "fire proof" construction to provide public safety against fire from secondary earthquake effects. Secondary effects are difficult to prevent through land-use practice although attempts made through appropriate construction practice are effective in controlling earthquake effects. Limiting occupancy types or densities in regions of high probable risk of ground failure is a viable option for land-use planning.

4) Infrastructure relates to protection of water supply, sewerage systems, roads, communications, and pipe lines to sustain economic stability in the community. The possibility of water supply backup systems or insuring against contamination may be critical to rapid recovery. Sewage pumping capacity should be maintained to prevent

disease. These options may apply to identification of earthquake hazard localities. Within such regions for which risk levels are high, special attention may be given to design requirements to prevent loss.

(c) Adoption of land-use strategies for mitigation is dependent upon local and state government, encouraged by public support. The will and desire for earthquake safety may be publicly provided but if economic pressures exist due to the perception of increased or unreasonable costs the power of public support may be negated. Creation of political backing for adopting earthquake mitigation strategies with public support is achieved through a systematic effort to clearly quantify the risks and associate costs.

The adoption procedure should be implemented by the local community with guidance and input from technical sources including federal agencies, state government, and regional advisory bodies consisting of engineers and geologists/seismologists. Through available input of the estimated risk, local officials and land-use planners will be provided an opportunity to determine acceptable risk for the community (assumed risk can not be less than minimum requirements prescribed by the applicable building code). Risk levels may be considered in terms of potential building loss translated into resulting human and economic loss if desired as a product of the planning process. The need for this evaluation is not site specific (the costs associated with determination of risk and safety requirements at each building site is excessive for local communities to perform). Site developers and owners must assume the responsibility for the design of their buildings. The determination of potential risk levels should be performed as a regional research project within a given region's earthquake safety preparedness plan.

The derived data and risk estimates may be used by local planners and building officials as they include earthquake hazards in the planning process to regulate or suggest acceptable risk for development within localities of the city.

The earthquake safety criteria in the building code for a given region is based on estimated risk zones (isoseismals) giving design requirements for the potential earthquake risk levels. It should remain a primary objective to update seismic code provisions and to achieve consistency in seismic design standards in the Central United States. Adoption of the NEHRP provisions (7) is encouraged. Nevertheless, it must be recognized that building codes in the Central United States do not include risk conditions for ground failure. Provisions for risk due to ground failure may be applied by local officials and land-use planners. If lower risk levels are adopted by owners/developers than suggested by building officials, it may be possible to influence safety in design through increased insurance rates or by denial of complete insurance coverage because of increased hazard levels, or by applying incentives. Of course, more rigid positions may be assumed by officials in attempting to achieve earthquake safety. The adoption of this plan should be left to the discretion of the local community as they consider community safety provided by satisfying the minimum conditions of the applicable building code.

(d) Non-structural issues of design and construction in buildings are critically involved in damage levels effecting life safety and economic loss (6). The imposition of safety requirements for non-structural conditions are best applied through the building code combined with public awareness rather than through local ordinances. Adoption of safety by applying building code provisions should consider the hazards:

1. Storage of hazardous materials including chemicals,
2. Bulk storage of free standing equipment and apparatus,
3. Hanging fixtures and suspended ceilings,
4. Critical lifeline facilities including banking and insurance data storage and processing systems,
5. Industrial and commercial facilities.

The application of safety standards are made by encouraging anchorage provisions suggested in general terms to provide desired performance against collapse. These guidelines may be incorporated as safety regulations possibly within the building code and enforced by local or state building officials. Building codes may adopt certain requirements through regulatory building drift limitations or by regulations on freely hanging permanent building fixtures. Storage of material or placement of furniture and equipment are not readily protected against earthquake damage through the building code and may best be handled by public awareness and public information guidelines.

Procedure

Earthquake mitigation practice follows standard procedures:

1. Research - The generation of new knowledge and its correlation with existing knowledge,
2. Translation - The synthesis of knowledge through intermediaries into forms that provide a basis for making decisions, and
3. Application - The adoption by decision makers at the community level to produce mitigation actions.

The outline for mitigation presented in this paper establishes a procedure that conforms to this practice. The procedure provides for:

1. Evaluation of source zone arrays for expected peak levels of seismicity.
2. Estimation of attenuation functions for regions of high risk.
3. Expected ground shaking and ground accelerations or displacements at these regions.
4. Estimation of probable soil failure through liquifaction or landslide.
5. Translation of seismic hazards to possible effects on buildings and establishment of risk levels in a community through research.
6. Incorporation of data into local planning and decision making functions through adoption of a land-use seismic safety element applying the risks and costs.
7. Active pursuit for incorporation of a consistent building code into the plan.
8. Adoption and implementation through local decision making based on comparison of risk levels using the seismic safety element (in 6 above) or the applicable building code (in 7). Use of the building code is the minimum safety measure to be applied. If the building code is not expected to insure against loss due to ground failure, the land-use seismic safety element may be applied by the locality planners and officials.

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DEVELOPING A COMPUTER-ASSISTED SEISMIC RISK ASSESSMENT MODEL FOR THE NEW MADRID EARTHQUAKE ZONE*

by

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INTRODUCTION

The New Madrid fault system, which is one of the more active and potentially one of the most dangerous tectonic features in the United States, has been the source of several damaging earthquakes since the early 19th century. Any planning for future events will be based largely on past events and continued research into the conditions governing tectonic activity and its effects on the area of concern. Since the rock units involved in New Madrid tectonics occur at depth, the source of the hazard is not easily studied at the surface.

This paper discusses a computer model designed to assess the relative seismic risk in west Kentucky using past epicenters and intensities, depth to the Paleozoic bedrock surface, and surface topography as information layers in a geographic information system. Most of the data extracted for sub-regional analysis pertains to the Murray, Calloway County, Kentucky area. The final product is a model of relative exposure (i.e., relative risk) of parts of the study area to past earthquake activity, perhaps as a basis for anticipating future destructive potential and areal disaster response for the west Kentucky portion of the New Madrid Earthquake Zone.

*The basic concept statement discussed in this paper was developed while Mr. Chernoff was a graduate student in the Department of Geosciences at Murray State University.

DATA ACQUISITION

Four layers of information were used in the stages of constructing computer seismic risk models. A fifth "critical facilities" layer was added for disaster response planning purposes. The first two layers were based on the geographic distance of a point to a given epicenter of 11 of the most significant historic New Madrid Seismic events (Nuttli, 1982).

The first distance model for the region was formed by creating a georeferenced data file that contained all 11 epicenters and computing the distance to the nearest epicenter on a pixel by pixel basis. This procedure produced a data layer of combined distance to epicenters for each pixel in the west Kentucky study area.

A second procedure using distances to epicenters produced a "summed exposure" model where each epicenter was treated separately, based on the relative magnitude of the event. The distances to each epicenter were then summed over all 11 epicenters (see Figure 1).

A third level of information, depth to the Paleozoic bedrock surface, was created and used for the Murray area. These data were compiled by subtracting digitized Paleozoic surface trend data (Schwalb, 1969) from U.S.G.S. 1:250,000 digital elevation data (National Cartographic Information Center, 1982).

The geophysical literature suggest that the effect of passing waves is determined largely by the structure of the rocks through which the waves pass. Earthquakes in the New Madrid system have been felt as far away as the East Coast while comparable quakes in California's San Andreas fault system have had considerably more localized effects due to differences in the geology of

Figure 1. Regional, Weighted, Summed Effects of the 11 Most Intense Events New Madrid Fault Zone. Note St. Louis and the outline of the Jackson Purchase region of west Kentucky for orientation and reference. Murray is in the eastern most portion of this region.

the two areas. At any particular point, when there are thick sequences of loosely compacted sediment such as those in the Mississippi River system, ground shaking is intensified. The occurrence is often referred to as "the jello bowl effect" (Griggs and Gilchrist, 1983). The depth to the Paleozoic bedrock surface was used as a parameter relating surface effects of waves to geology in the west Kentucky region. No geological effects on passing of waves were considered in weighting the distance levels. Geophysical information on the ability of rock units to transmit waves could be of value in modifying the distance-based data levels, as the structure of rocks that waves pass through to reach any given point could affect information based purely on distance (Spencer, 1977). Reliable data of this type would be difficult to incorporate into a geographic information system on a pixel by pixel basis.

Digital surface slope data computed from the U.S.G.S. digital elevation data was used as the fourth level of information. It was included because areas of high surface slope may be unstable and more hazardous in the event of an earthquake than surrounding flat or gently sloping areas (Griggs and Gilchrist, 1977).

A fifth level of information was incorporated as a discrete "critical facility" overlay for the Murray area. This overlay included major highways, urbanized areas, utilities, etc., and was acquired through digitization from a 1:250,000 U.S.G.S topographic map.

DATA PROCESSING

All data processing and analysis was accomplished at the Mid-America Remote Sensing Center, Murray State University. All visual analysis was done on a

COMTAL image processing system using the Earth Resources Laboratory Applications Software (ELAS) (Graham, et al., 1980). The main processor was the Univac V77-612 computer. Digitization was performed on the Talos SBL661 digitizer.

Construction Of Data Layers

The data layers used in this study, as previously mentioned, included distance from past epicenters (combined distance), distance from past epicenters weighted by the events intensity (summed exposure), depth to bedrock, and slope. It was necessary to use a file covering the entire region for the combined distance and summed exposure layers because the 11 epicenters were a considerable distance from the Murray area. These files were created with a large pixel size (240 meters) in order to have a manageable file size and reduce calculation time. The final data file for the sub-regional analysis contained the four primary layers, each with a 60 meter pixel size.

For the combined distance data layer, epicentral coordinates given in latitude and longitude were converted to UTM grid zone 16 coordinates using ELAS module CVRT. These epicenters were then "turned on" in an ELAS data file that was given a georeferenced header representing the entire study region. Once the pixels representing epicenters were given the epicentral value, module DIST of ELAS was run to compute the distance from each pixel to the nearest epicenter. This data file was then ready for later extraction of the Murray study area for use with other data, and for the updating of digitized political boundaries in the Jackson Purchase as reference.

A similar procedure was followed for the summed exposure model. In this case, however, only one pixel representing an epicenter was "turned on" for each run of DIST. After each run of DIST, the values were scaled down to allow for the accumulation of 11 different runs of DIST, one for each epicenter, in a separate accumulator file, where each pixel can represent values only up to 255. The values assigned by DIST in each run were weighted to allow for variations in the magnitude of different events. The resultant file showed the effects of the larger events decreasing less with distance than the effects of the smaller events. This weighting could not be done with the combined model and allowed for individual treatment of epicenter coordinates based on previously displayed intensities.

Once the regional files were created, the Murray study area was extracted and resampled from 240 meter pixels to 60 meter pixels to be compatible with other data layers that cover the Murray study area. A portion of each regional file was also extracted that focused on west Kentucky and the relative effects of epicenters on the region for each model.

The remaining data layers for the Murray study area were created from digitized Paleozoic surface elevation data and digital surface elevation data at a scale of 1:250000 which is distributed by the U.S.G.S. (National Cartographic Information Center, 1982). ELAS module TOP6 was used to derive slope information from the digital data for the Murray study area. Using module DBAS, the Paleozoic surface values were subtracted from the surface elevation values to determine depth to bedrock. This computed depth information could then be used with the two distance related layers for inclusion in the models.

Construction Of Models

Each model was formed by scaling the range of values from 1 to 30 for each layer, so that each would contribute evenly, and then using ELAS module DBAS to execute the formula for each pixel. Once models were formed for the Murray study area, the digitized cultural features were updated to the data files.

SUMMARY AND RECOMMENDATIONS

In both distance related layers, distance effects in west Kentucky have a strong west to east trend. In the combined distance model, the trend is due to the proximity of events across the Mississippi in Missouri. In the summed exposure model (see Figure 2), the west to east trend is largely due to the higher intensity of the events to the west, which also are nearest the study area. This would not necessarily be the case in other areas where relative distances and intensities would be different.

The depth to bedrock layer also has a strong, shallowing west to east trend. Due to the low resolution of the digitized data, strong banding is apparent with local variations due to surface topography. Detailed geologic data would improve the information content of the depth to bedrock layer. However, the only information available is interpolated from scattered cores (Schwalb, 1969). It would be expected that models using two such highly correlated data sets would show a similar trend. The strong west to east trend is visible in all models. When the slope data is entered, areas of highest slope produce regional variation within the general west to east trend, thus denoting localized "hazardous areas" based on the surface slope. These areas are visible in all models that include slope (see Figure 2).

Figure 2. Hazard Model Including Summed Exposure, Depth to Bedrock, and Slope data layers, Murray area, west Kentucky. Lighter tones depict areas of lowest hazard.

In analyzing the information present in these models, it is important to realize that they represent <u>relative</u> effects based on epicentral coordinates. Although the resolution of the geologic data is low, enough information is present to observe general trends. With this in mind, conclusions should only be drawn on a relative basis.

The relationship between earthquakes and their effect on future faulting is highly unpredictable, although not entirely random, even when faults are exposed on the surface (Griggs and Gilchrist, 1983). The occurrence of an earthquake at one location changes the stress characteristics of the rock units in the surrounding area. Therefore, future occurrences of earthquakes will occur under somewhat different conditions.

Although some geophysical research has been conducted, the New Madrid system is still poorly understood, and reliable predictive power would be elusive even if the faulting occurred at the surface (McKeown, 1982). It may be tempting to consider past events as a sample of all possible events, however, forces involved in crustal deformation are interrelated. The occurrence of an earthquake at one location affects the forces involved in the area as a whole, as tension in rock units is released (Spencer, 1977). Although certain areas may show a high concentration of past faulting activity, the complex nature of the New Madrid system makes reliance on the past somewhat uncertain. Nevertheless, geographic information systems can be a useful tool in modeling effects and relationships for planning purposes, although the lack of data and understanding of the forces at work may well limit the reliability of any predictions.

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TECHNICAL ASPECTS OF SEISMIC MICROZONATION

by

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ABSTRACT

Seismic microzonation, the division of a region into areas expected to experience physical effects of the same relative severity during an earthquake, is a part of the process of evaluating the earthquake hazards of a region. Although seismic microzonation has been performed worldwide, no standard method currently exists for Performing these studies. Consequently, seismic microzonation requires careful integration of geologic and seismological data on regional and urban scales to achieve the optimum results. Seismic microzonation studies are feasible in at least a preliminary way in many parts of the United States and have many potentially useful applications.

INTRODUCTION

Seismic microzonation, the division of a region into smaller areas expected to experience the same relative severity of an earthquake hazard (for example, ground shaking, surface fault rupture, earthquake-induced ground failure, tectonic deformation, or tsunami runup) is an important part of the process of evaluating earthquake hazards. Seismic microzonation is the part of the process of evaluating earthquake hazards that provides the prospective user of an area with the design criteria that will permit selection of the most suitable part of the area for the proposed use (Borcherdt, 1975). Applications of seismic microzoning maps are typically made in terms of land-use, building codes (Applied Technology Council, 1978; Uniform Building code, 1983), construction practices, and repair and strengthening of existing buildings. Seismic microzonation derives design criteria by obtaining explicit answers to the questions:

-- Where are the earthquakes occurring now? Where did they occur in the past?
-- Why are they occurring?
-- How often do earthquakes of a certain size (magnitude) occur?
-- How big (severe) have the physical effects been in the past. How big can they be in the future (e.g., the next 50 years)?
-- How do the physical effects vary spatially and temporally?

Although these questions appear to be simple, the answers typically require detailed technical studies that integrate geologic and seismological data on two scales:

1) Evaluation of seismic hazards on a regional scale: (a map scale of about 1:100,000 to 1,250,000). This part of a microzoning study establishes the physical parameters of the region needed to evaluate the earthquake hazards of ground shaking, surface fault rupture, tectonic deformation, and tsunami runup. Technical task such as the following are required:

-- Compilation of a catalog and map of the prehistorical, historical, and current seismicity.
-- Performance of neotectonic studies (mapping, age dating, and trenching) to acquire information on recurrence times in the past several thousand years not provided by historical seismicity.
-- Preparation of a seismotectonic map showing the location of active faults and their correlation with seismicity.
-- Preparation of a map showing seismogenic zones and giving the magnitude of the maximum earthquake and the frequency of occurrence for each zone.
-- Specification of regional seismic wave attenuation laws and their uncertainty
-- Preparation of probabilistic ground-shaking hazard maps in terms of peak bedrock acceleration, peak bedrock velocity, exposure times, and probabilities of nonexceedance.

2) Evaluation of seismic hazards on an urban scale: (a map scale of about 1:5,000 to 1:25,000). This part of a microzonation study integrates the seismotectonic and other physical data acquired in the regional study

(Part 1) with site-specific data acquired in the urban area to produce seismic microzonation maps. Technical tasks such as the following are required:

-- Acquisition, synthesis, and integration of existing and new geologic, geophysical, and geotechnical data to characterize the soil/rock columns in terms of their physical properties and their response to various levels of ground shaking.

-- Preparation of ground-shaking hazard maps showing the dynamic amplification factors for soil/rock columns in terms of amplitude and frequency composition of ground shaking and the level of dynamic shear strain.

-- Preparation of a map showing the potential for surface fault rupture and tectonic deformation.

-- Preparation of a map showing the potential for liquefaction.

-- Preparation of a map showing the potential for landslides.

TECHNICAL PROBLEMS

Microzonation on both a regional and an urban scale requires the best available information on 1) seismicity, 2) the nature of the earthquake source zone, 3) seismic wave attenuation, and 4) local ground response. A number of technical issues (i.e., questions for which expert judgment is divided between "yes" and "no") have been identified for the problem of microzoning the ground-shaking hazard. They are summarized below to provide examples of their range and complexity.

Seismicity - The record of historical seismicity throughout the United States varies considerably in length and completeness. Lack of completeness can introduce biases in statistical analyses unless careful judgments are made. For example, incorporating geologic evidence of recent faulting as well as geodetic data improves the likelihood of establishing the best possible recurrence rates for earthquakes (Sieh, 1978; Russ, 1981; Bucknam and Anderson, 1981). If geologic and geophysical data are not available, it may be extremely difficult to estimate the maximum magnitude in an area, and indeed, it is possible that a number of geographic areas may not have experienced their maximum magnitude earthquake. That is, the record of historical seismicity alone may cause the maximum magnitude to be underestimated.

The issues include the following:

-- Will the uncertainty involved in using catalogs of instrumentally recorded and felt earthquakes representing a short time interval and a broad regional area permit a precise specification of the frequency of recurrence of major earthquakes on a local scale?

-- Can the seismic cycle of individual fault systems be determined accurately and, if so, can we specify where we are in the cycle?

-- Can the location and magnitude of the largest earthquake that is physically possible on an individual fault system or in a seismotectonic province be specified accurately? Can the frequency of this event be specified?

-- Can seismic gaps be identified and their earthquake potential evaluated accurately?

-- Can discrepancies between the geologic evidence for the occurrence of major tectonic movements in the geologic past and the evidence provided by current and historic patterns of seismicity in a geographic region be reconciled?

Earthquake Source Zones - No standard method has been adopted for delineating seismic source zones. Usually, each cluster of earthquake foci or active faults is considered as a source zone; however, scientific judgment is involved in drawing the boundaries of source zones. For example, one danger is that two or more regions having different seismotectonic characteristics will be inadvertently combined and the resultant analysis will suggest some average but nonexistent physical condition. In defining seismic source zones, all available information is used to establish the physical correlations between earthquake occurrences and geologic processes and tectonic structures, including: (1) location of the boundaries of crustal blocks which are undergoing contrasting displacements, (2) history of vertical and horizontal regional tectonic movements, (3) the seismic cycle and history of active faults, and (4) tectonic stress. Each seismic source zone is chosen so that it encloses an area of seismic activity and, to the extent possible, an area of related tectonic elements (Algermissen and Perkins, 1976). Earthquakes are commonly assumed to be equally likely anywhere in a source zone, to have an average rate of occurrence that is constant in time, and to follow a Poisson distribution of recurrences. In 1976, Algermissen and Perkins identified 71 seismic source zones for the United States. These zones were subsequently refined and now the number exceeds 100 (Algermissen and others, 1982).

The technical issues include the following:

-- Can seismic source zones be defined accurately on the basis of historic seismicity? On the basis of geology and tectonics? On the basis of historical seismicity generalized by geologic and tectonic data? Which approach is most accurate?

-- In assessing the earthquake ground-shaking hazard for a region, can a magnitude be assigned accurately to the largest earthquake expected to occur in a given period of time on a particular fault system or in a seismic source zone?

-- Can the physical effects of earthquake source parameters such as stress drop and seismic moment be quantified and incorporated in zoning maps?

Seismic Wave Attenuation - Characterization of the ground motion close to an active fault is one of the most difficult parts of the problem of constructing a ground-shaking hazard map. The empirical data are currently too limited to resolve all of the technical issues concerning the attenuation characteristics of both near- and far-field ground motion, even though unique ground-motion data were acquired in the 1979 Imperial Valley, California, earthquake. These data reinforced current thinking in some areas and revised it in other areas, but did not resolve all of the controversial issues concerning seismic wave attenuation. Because current knowledge of the frequency-dependent effects of the transmission path on earthquake ground motion is inadequate, these effects are somewhat uncertain and controversial. Applications requiring frequency-dependent information are based on observational and instrumental data which indicate that the regional seismic attenuation rates depend on the physical properties (i.e., Q structure) of the Earth's crust and upper mantle in a region, that the attenuation rates can vary considerable from region to region, and that Q is frequency dependent (Singh, 1981).

Attenuation curves specifying how values of peak ground motion decrease as distance from the causative fault increases are required in zoning. Such curves are essential when constructing a zoning map of the peak-acceleration ground-shaking hazard. The problem is that many attenuation curves having substantial differences exist in the literature. Some researchers feel that some of these curves may underestimate the maximum acceleration and that the suggestion of a dependence on magnitude is still an open question. The question of magnitude dependence of attenuation is important in probabilistic hazard estimation because it sharply influences the estimated level of maximum ground motion in two cases: 1) areas of high seismicity, and 2) or when long periods of time are considered.

The technical issues include:

-- Can the complex details of the earthquake fault rupture (e.g., rupture dimensions, fault type, fault offset, fault slip velocity) be modeled accurately enough to give precise estimates of the amplitude and frequency characteristics of ground motion close to the fault? Far from the fault?

-- Do peak ground-motion parameters saturate at large magnitudes?

Local Ground Response - Technical literature of earthquake engineering and engineering seismology since the early 1900's has recognized and documented that structures founded upon unconsolidated material (soil) are damaged, more frequently in earthquakes than structures founded and rock. More important, the damage distribution on many occasions (for example, in the 1967 Caracas, Venezuela, and the 1985 Mexico earthquakes) has been recognized as being site related. Many past studies (see Hays, 1980 for a summary) have used ground-motion data to define the frequency-dependent ground response of local areas. In these and other studies, researchers have shown that the transfer function, defined as the average ratio of the 5 percent damped, horizontal velocity response spectra for a pair of sites) is a function of the shear-wave velocity, thickness, water content, and geometry of the soil and rock column underlying the area. Rogers and Hays (1978) suggested an important research result; namely, that the horizontal transfer function for some soil types is repeatable and can be determined fairly accurately from ground-motion data, even though the data represent a wide range in levels of peak ground acceleration and dynamic shear strain (defined as the ratio of the peak velocity recorded at the site to the shear-wave velocity of the near-surface material underlying the site). The question of strain dependence is still controversial; only acquisition of ground-motion data recorded at sites underlain by rock and a variety of soil columns close to the fault from large to great earthquakes will resolve the current arguments.

The technical issues include the following:

-- For various soil types, is there a discrete range of peak ground-motion values and levels of dynamic shear strain where the ground response (as defined by a site transfer function) is repeatable and essentially linear? Is there a range where nonlinear effects dominate? Is there a range where nonlinear effects dominate?

-- Can the physical effects of selected physical properties of the soil and rock column (e.g., thickness, lithology, geometry, water content, shear-wave velocity, and density) be modeled accurately? Which of these physical properties control the spatial variation, duration, and amplitude and spectral characteristics of ground response in a geographic region?

-- Can the variation of ground motion with depth below the surface be modeled accurately in order to estimate the ground-shaking hazard to underground facilities?

-- Is the uncertainty associated with a site transfer function small at all levels of ground-shaking or does it vary as a function of magnitude?

SEISMIC MICROZONATION IN THE CENTRAL UNITED STATES

In spite of the large number of technical issues that have not yet been completely resolved, seismic microzonation is feasible in at least a preliminary way in the Central United States. It seems clear that current zoning maps of the ground-shaking hazard based on Modified Mercalli intensity, or a peak ground-motion parameter can be improved. The best option for improvement is to incorporate frequency-dependent effects related to: 1) the mechanics of fault rupture, 2) earthquake source parameters, 3) the geology along the transmission path, and 4) the soil and rock columns underlying the construction site. One option for improving ground-shaking hazard maps is to incorporate the effects of soil and rock columns underlying the area, using the available ground-motion data base to characterize the average response expected for certain soil types under various levels of ground shaking (Seed and Idriss, 1982). This step would serve to delineate the zones that are expected to experience the greatest severity of ground shaking. Such microzonation maps would be more physically correct, and would, potentially, have a wider range of applications that zoning maps based on a single parameter of peak-ground motion, intensity, or assumptions about the underlying bedrock.

Zoning maps which incorporate site effects can be used to guide land-use planning and earthquake-resistant design. Criteria for their use might be stated in the context of the earthquake that is expected to occur, for example, on the average, once every 50 years, --the average life time of an ordinary building.

Zoning maps of the ground-shaking hazard which incorporate frequency-dependent effects caused by the local geology are currently controversial, primarily because of the limitations of the available empirical ground motion data. The existing data are inadequate to resolve the controversy associated with certain technical issues such as high-strain ground shaking. The question of the dependence of a transfer function on the level of dynamic shear strain is an old and important question that still has not been resolved. Some insight can be gained into the high-strain issue by using velocity seismograms derived from accelerograms of prior earthquakes in conjunction with the shear-wave velocity of various surficial materials (Ambraseys, 1973). These data can be used to estimate the strain level induced in the soil and rock column by calculating the ratio of the peak particle velocity to the shear-wave velocity of the material underlying the site. On the basis of the available data, the greatest level of dynamic shear strain induced in soil and rock during past earthquakes (for which accelerograms were recorded) appears to be about 0.5 percent. Thus, the current data sample contains no records of high-strain ground shaking that correlates with that obtained in laboratory measurements. The lack of high-strain ground motion data is plausible when considered from the viewpoint of the regional attenuation relation for peak velocity and values of shear-wave velocity of soils. These data can be used to estimate the epicentral distance to specific levels of shear strain (e.g., 0.1 percent, 0.01 percent, etc.) in an earthquake. For surficial materials characterized by a shear wave velocity of 200 m/sec, the epicentral distance to the 0.1 percent level of shear strain is about 19 km; whereas, the distance to the 0.5 percent level of shear strain is about 2 km. If the level of 0.5 percent marks the approximate onset of significant nonlinear behavior (as suggested by data reported by Hays and others, 1979) at sites underlain by unconsolidated material, the portion of the epicentral zone where high shear-strain effects can be recorded is fairly small. These data suggest that the task of incorporating local ground response in ground-shaking hazard maps is probably more feasible than generally thought, except possibly within a few kilometers of the fault zone of a large to great-magnitude earthquake, and that empirical data representing conditions of high-strain ground shaking may be very difficult to acquire.

POTENTIAL APPLICATIONS OF SEISMIC MICROZONATION MAPS

Applications of seismic microzonation maps can be made in terms of land-use, building codes, construction practices, and repair and strengthening of existing buildings. Technical applications include:

-- Evaluation of the current building code, identifying options for modifications that incorporate the scientific and engineering lessons learned from past destructive earthquakes.

-- Evaluation of regional and urban land-use practices, identifying options for alternatives to current practices that might reduce potential losses.

-- Evaluation of construction practices for new buildings, specifying options for alternatives to current practices that might be more effective in ensuring high quality.

-- Evaluation of the current practices to repair and strengthen existing buildings, suggesting options for alternatives to current practices that might be more effective.

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APPENDIX A

GLOSSARY OF TERMS USED IN EARTHQUAKE HAZARDS ASSESSMENTS

Accelerogram. The record from an accelerometer showing acceleration as a function of time. The peak acceleration is the largest value of acceleration on the accelerogram.

Acceptable Risk. A probability of occurrences of social or economic consequences due to earthquakes that is sufficiently low (for example in comparison to other natural or manmade risks) as to be judged by appropriate authorities to represent a realistic basis for determining design requirements for engineered structures, or for taking certain social or economic actions.

Active fault. A fault is active if, because of its present tectonic setting, it can undergo movement from time to time in the immediate geologic future. This active state exists independently of the geologists' ability to recognize it. Geologists have used a number of characteristics to identify active faults, such as historic seismicity or surface faulting, geologically recent displacement inferred from topography or stratigraphy, or physical connection with an active fault. However, not enough is known of the behavior of faults to assure identification of all active faults by such characteristics. Selection of the criteria used to identify active faults for a particular purpose must be influenced by the consequences of fault movement on the engineering structures involved.

Asthenosphere. The worldwide layer below the lithosphere which is marked by low seismic wave velocities. It is a soft layer, probably partially molten.

Attenuation law. A description of the average behavior of one or more characteristics of earthquake ground motion as a function of distance from the source of energy.

Attenuation. A decrease in seismic signal strength with distance which depends not only on geometrical spreading, but also may be related to the physical characteristics of the transmitting medium that cause absorption and scattering.

b-value. A parameter indicating the relative frequency of earthquakes of different sizes derived from historical seismicity data.

Capable fault. A fault along which future surface displacement is possible, especially during the lifetime of the engineering project under consideration.

Convection. A mechanism of heat transfer through a liquid in which hot material from the bottom rises because of its lesser density, while cool surface materials sinks.

Convergence Zone. A band along which moving plates collide and area is lost either by shortening and crustal thickening or subduction and destruction of crust. The site of volcanism, earthquakes, trenches, and mountain building.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology used for the earthquake-resistant design of a structure.

Design spectra. Spectra used in earthquake-resistant design which correlate with design earthquake ground motion values. Design spectra typically are smooth curves that take into account features peculiar to a geographic region and a particular site.

Design time history. One of a family of time histories used in earthquake-resistant design which produces a response spectrum enveloping the smooth design spectrum, for a selected value of damping.

Duration. A qualitative or quantitative description of the length of time during which ground motion at a site exhibits certain characteristics such as being equal to or exceeding a specified level of acceleration such as 0.05g.

Earthquake hazards. The probability that natural events accompanying an earthquake such as ground shaking, ground failure, surface faulting, tectonic deformation, and inundation, which may cause damage and loss of life, will occur at a site during a specified exposure time. See earthquake risk.

Earthquake risk. The probability that social or economic consequences of earthquakes, expressed in dollars or casualties, will equal or exceed specified values at a site during a specified exposure time.

Earthquake waves. Elastic waves (P, S, Love, Rayleigh) propagating in the Earth, set in motion by faulting of a portion of the Earth.

Effective peak acceleration. The peak ground acceleration after the ground-motion record has been filtered to remove the very high frequencies that have little or no influence upon structural response.

Elastic rebound theory. A theory of fault movement and earthquake generation that holds that faults remain lock while strain energy accumulates in the rock, and then suddenly slip and release this energy.

Epicenter. The point on the Earth's surface vertically above the point where the first fault rupture and the first earthquake motion occur.

Exceedance probability. The probability (for example, 10 percent) over some period of time that an event will generate a level of ground shaking greater than some specified level.

Exposure time. The period of time (for example, 50 years) that a structure is exposed to the earthquake threat. The exposure time is sometimes related to the design lifetime of the structure and is used in seismic risk calculations.

Fault. A fracture or fracture zone in the Earth along which displacement of the two sides relative to one another has occurred parallel to the fracture. See Active and Capable faults.

Focal depth. The vertical distance between the hypocenter and the Earth's surface in an earthquake.

Ground motion. A general term including all aspects of motion; for example, particle acceleration, velocity, or displacement; stress and strain; duration; and spectral content generated by a nuclear explosion, an earthquake, or another energy source.

Intensity. A numerical index describing the effects of an earthquake on the Earth's surface, on man, and on structures built by him. The scale in common use in the United States today is the Modified Mercalli scale of 1931 with intensity values indicated by Roman numerals from I to XII. The narrative descriptions of each intensity value are summarized below.

I. Not felt--or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds and animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body of striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink or clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practially all, outdoors by many or most; outdoors direction estimated. Awakened many or most. Frightened few--slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes and glassware to some extent. Cracked windows--in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors and shutters abruptly. Pendulum clocks stopped, started or ran fast, or slow. Move small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees and bushes shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees and bushes shaken slightly to moderately. Liquid set in strong motion. Small bells rang--church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knickknacks, books, pictures. Overturned furniture in many instances. Move furnishings of moderately heavy kind.

VII. Frightened all--general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows and furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general--alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly--branches and trunks broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse, racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls, cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changes level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipelines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft, wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures, remained standing. Destroyed large well-built bridges by the wrecking of supporting piers or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipelines buried in each completely out of service.

XII. Damage total--practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

Liquefaction. Temporary transformation of unconsolidated materials into a fluid mass.

Lithosophere. The outer, rigid shell of the earth, situated above the asthenosphere containing the crust, continents, and plates.

Magnitude. A quantity characteristic of the total energy released by an earthquake, as contrasted to intensity that describes its effects at a particular place. Professor C. F. Richter devised the logarithmic scale for local magnitude (M_L) in 1935. Magnitude is expressed in terms of the motion that would be measured by a standard type of seismograph located 100 km from the epicenter of an earthquake. Several other magnitude scales in addition to M_L are in use; for example, body-wave magnitude (m_b) and surface-wave magnitude (M_s), which utilize body waves and surface waves, and local magnitude (M_L). The scale is open ended, but the largest known earthquake have had M_s magnitudes near 8.9.

Mantle. The main bulk of earth between the crust and core, ranging from depths of about 40 to 2900 kilometers.

Mid-oceanridge. Characteristic type of plate boundary occurring in a divergence zone, a site where two plates are being pulled apart and new oceanic lithosphere is being created.

Plate tectonics. The theory and study of plate formation, movement, interaction, and destruction.

Plate. One of the dozen or more segments of the lithosphere that are internally rigid and move independently over the interior, meeting in convergence zones and separating in divergence zones.

Region. A geographical area, surrounding and including the construction site, which is sufficiently large to contain all the geologic features related to the evaluation of earthquake hazards at the site.

Response spectrum. The peak response of a series of simple harmonic oscillators having different natural periods when subjected mathematically to a particular earthquake ground motion. The response spectrum may be plotted as a curve on tripartite logarithmic graph paper showing the variations of the peak spectral acceleration, displacement, and velocity of the oscillators as a function of vibration period and damping.

Return period. For ground shaking, return period denotes the average period of time or recurrence interval between events causing ground shaking that exceeds a particular level at a site; the reciprocal of annual probability of exceedance. A return period of 475 years means that, on the average, a particular level of ground motion will be exceeded once in 475 years.

Risk. See earthquake risk.

Rock. Any solid rock either at the surface or underlying soil having a shear-wave velocity 2,500 ft/sec (765 m/s) at small (0.0001 percent) strains.

Sea-floor spreading. The mechanism by which new sea floor crust is created at ridges in divergence zones and adjacent plates are moved apart to make room.

Seismic Microzoning. The division of a region into geographic areas having a similar relative response to a particular earthquake hazard (for example, ground shaking, surface fault rupture, etc.). Microzoning requires an integrated study of: 1) the frequency of earthquake occurrence in the region, 2) the source parameters and mechanics of faulting for historical and recent earthquakes affecting the region, 3) the filtering characteristics of the crust and mantle constituting the regional paths along which the seismic waves travel, and 4) the filtering characteristics of the near-surface column of rock and soil.

Seismic zone. A generally large area within which seismic design requirements for structures are uniform.

Seismotectonic province. A geographic area characterized by similarity of geological structure and earthquake characteristics. The tectonic processes causing earthquakes have been identified in a seismotectonic province.

Source. The source of energy release causing an earthquake. The source is characterized by one or more variables, for example, magnitude stress drop, seismic moment. Regions can be divided into areas having spatially homogeneous source characteristics.

Strain. A quantity describing the exact deformation of each point in a body. Roughly the change in a dimension or volume divided by the original dimension or volume.

Stress. A quantity describing the forces acting on each part of a body in units of force per unit area.

Strong motion. Ground motion of sufficient amplitude to be of engineering interest in the evaluation of damage due to earthquakes or in earthquake-resistant design of structures.

Subduction zone. A dipping planar zone descending away from a trench and defined by high seismicity, interpreted as the shear zone between a sinking oceanic plate and an overriding plate.

Transform fault. A strike-slip fault connecting the ends of an offset in a mid-ocean ridge. Some pairs of plates slide past each other along transform faults.

Trench. A long and narrow deep trough in the sea floor; interpreted as marking the line along which a plate bends down into a subduction zone.

Triple junction. A point that is common to three plates and which must be the meeting place of three boundary features, such as convergence zones, divergence zones, or transform faults.

APPENDIX B

EARTH SCIENCE CONSIDERATIONS FOR EARTHQUAKE
HAZARDS REDUCTION IN THE CENTRAL UNITED STATES
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APPENDIX C

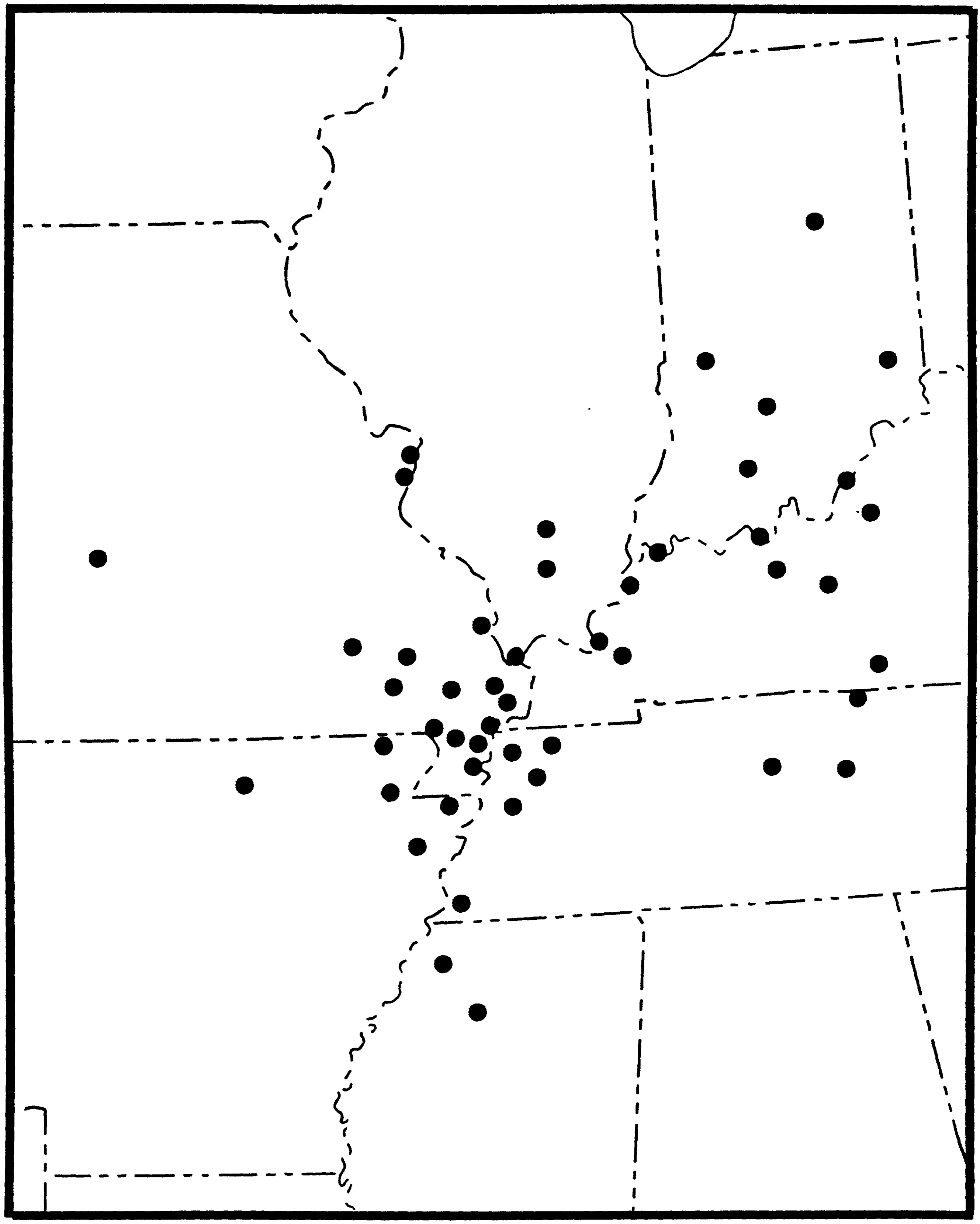
LOCATION OF STRONG MOTION INSTRUMENTS IN THE CENTRAL UNITED STATES
USGS COOPERATIVE NETWORK

STATION	ACCELEROGRAPHS	OWNER*
Arkansas		
Blytheville	1	USGS
Corning	1	USGS
Lepanto	1	USGS
Norfolk Dam	2	COE
Paragould	1	USGS
Illinois		
Cairo	1	USGS
Marion, V.A.	1	USGS
Rend Lake Dam	3	COE
Smithland Lock & Dam	5	COE
Indiana		
Brookville Dam	3	COE
Cagles Mill Dam	3	COE
Cannelton Dam	2	COE
Marion V.A. Hospital	1	VA
Monroe Lake Dam	3	COE
Newburgh Dam	2	COE
Patoka Dam	2	COE
Uniontown Dam	2	COE
Kentucky		
Barkley Dam	6	COE

Kentucky cont.		
Louisville, V.A.	1	VA
Martins Fork Dam	4	COE
Nolin River Dam	3	COE
Rough River Dam	3	COE
Taylorsville Dam	3	COE
Wolf Creek Dam	5	COE
Mississippi		
Arkabutla Dam	3	COE
Sardis Dam	3	COE
Missouri		
Campbell	1	USGS
Cape Giradeau	1	USGS
Clearwater Dam	3	COE
Dexter	1	USGS
Gideon	1	USGS
Harry Truman Dam	2	COE
Hayti	1	USGS
Interstate 55/Route P	1	USGS
New Madrid	1	USGS
Poplar Bluff, V.A.	1	VA
Portageville	1	USGS
Sikeston	1	USGS
St. Louis, Cochran V.A.	1	VA
St. Louis, Jefferson V.A.	1	VA
Wappapello Dam	3	COE

Tennessee		
Center Hill Dam	5	COE
Dale Hollow Dam	5	COE
Dyersburg	1	USGS
Memphis V.A.	1	VA
Obion	1	USGS
J.P. Priest Dam	5	COE
Tiptonville	1	USGS
Union City	1	USGS

* COE Corps of Engineers
USGS U.S. Geological Survey
VA Veterans Administration



ACCELEROGRAPH STATIONS IN THE SEVEN-STATE UPPER MISSISSIPPI EMBAYMENT

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