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DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

A READER ON EARTHQUAKE HAZARD REDUCTION IN THE CENTRAL UNITED STATES

TO ACCOMPANY TRAINING COURSES

PRESENTED BY

THE U.S. GEOLOGICAL SURVEY

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THE CENTRAL UNITED STATES EARTHQUAKE CONSORTIUM

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AN ACTIVITY OF THE DECADE FOR NATURAL DISASTER REDUCTION

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COURSE 1

HAZARD AND RISK ASSESSMENT

II

A READER ON EARTHQUAKE HAZARD REDUCTION IN THE CENTRAL UNITED STATES

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PREFACE

INTERNATIONAL DECADE FOR NATURAL DISASTER REDUCTION

The concept of a Decade for Natural Disaster Reduction has evolved considerably since it was proposed by Dr. Frank Press, President of the U.S. National Academy of Sciences, in July 1984 at the Eighth World Conference on Earthquakes Engineering. Now, the United States and at least 28 other nations and organizations have taken steps to organize and plan for concerted national and international actions during the 1990's to reduce loss of life and economic losses from disasters triggered by natural hazards. Approximately 100 nations are expected to accept this goal and to join with the United States and others following the 43rd General Assembly of the United Nations in the fall of 1989. They are expected to forge unilateral, bilateral, and multilateral partnerships to make their country and the world safer from floods, windstorms (typhoons, cyclones, hurricanes, and tornadoes), landslides, earthquakes, volcanic eruptions, wildfires, tsunamis, drought, and insect infestation. These programs are expected to be multihazard, multifunctional, and multiorganizational in scope.

The United States, which faces annual losses of approximately $10 billion from the natural hazards listed above, is developing this program the Decade through a partnership involving:

- The Federal Agencies, which are organized through the Committee on Earth Sciences as the Subcommittee on Natural Disaster Reduction.

- The National Research Council of the National Academy of Sciences which has organized a U.S. National Committee on the Decade for Natural Disaster Reduction to advise the Federal Agencies.

- Institutions, organizations, and individuals having abroad range of expertise throughout the nation who have responded to an "Invitation to Participate in the Decade" extended by the U.S. National Committee in May 1989.

The U.S. National Committee, chaired by Dr. Richard Hallgren, American Meteorological Society, consists of 15 members having backgrounds and broad experience in the earth sciences, hydrology, wind engineering, earthquake engineering, fire safety, weather, political science, communication, insurance, the environment, emergency management, and public administration. The committee is supplemented by working members from and of the Federal Agencies having natural hazard programs (for example, U.S. Geological Survey, National Science Foundation, National Oceanic and Atmospheric Administration, Federal Emergency Management Agency, National Institute of Standards and Technology, the U.S. Forest Service, National Aeronautics and Space Agency, Office of U.S. Foreign Disaster Assistance, Corps of Engineers, and the State Department).

The Federal Agencies Subcommittee on Natural Disaster Reduction and the U.S. National Committee must deal with three critical problems in the development of a U.S. Decade program. The are:

- o Leadership,
- o Motivation, and
- o Funding.

Each of these complex problems is being addressed cooperatively. The goal of the cooperative efforts is to:

- o Develop a vision of where we go as a Nation during the decade.
- o Identify a rallying point that all participants in the Decade throughout the Nation can associate with (for example: a) zeal for protecting our planet from the disastrous consequences of natural hazards, b) personal pride in protecting our homes, families, and workplaces, c) national pride that comes from gaining a position of preeminence in the world in natural hazards research or in disaster prevention, and d) the challenge of working together to make the world safer and more productive).
- o Create partnerships at all levels throughout the Nation to carry out programs to accomplish the vision (for example: a) Federal-Federal, b) Federal-State, c) State-State, and d) Federal-regional partnerships).
- o Attack complex programmatic issues one step at a time(for example: a) the linkage between researchers and practitioners, and b) the interface between disciplines).
- o Work smarter, not just harder (for example: a) take advantage of the exiting body of fundamental knowledge on natural hazards developed through research, and b) utilize modern technology such as geographic information systems, satellites, and computer networks).
- o Communicate (for example: a) use a nationwide speakers bureau to communicate the vision of the Decade to everyone, b) use a national news letter, c) improve the capability of credible sources of hazards and risk information to use all of the available channels to reach decisionmakers and policymakers and their constituencies with a meaningful message).
- o Simplify (for example, some loss reduction techniques for each natural hazard can be applied to another natural hazard).
- o Evaluate (for example: a) use the anniversary dates of past notable disasters as a time to take stock of progress and to examine gaps in knowledge or capability and b) use each new

disaster as a window of opportunity to exiting capability).

These seven actions are expected to provide solutions to the problems associated with leadership, motivation, and funding.

The U.S. Committee, which met for the first time on June 21-22, 1989, will produce a comprehensive report in 1990 containing model programs and recommendations on how to implement them. These programs will call for:

- <u>Pilot projects</u> to build local, State, regional, and national partnerships,
- <u>National projects</u> to accelerate the application of loss reduction measures, and
- <u>International projects</u> to share the technology for hazard mitigation with other nations, especially developing countries.

The overall goal is to save lives and to reduce economic losses in the United States. The particular thrusts of the U.S. Decade programs will be on achieving:

- Coordination and integration of the natural hazard programs of the Federal Agencies, State and local governments, academia, and the private sector.
- Development of hazard warning and prediction systems.
- Creation and sharing of multihazard databases and mitigation techniques.
- Implementation of post disaster data acquisition, data analysis, and data sharing programs.
- Execution of research to close critical gaps in fundamental knowledge on topics such as extreme events and the implications of regionally and temporally varying natural hazards occurring singularly or in combinations.
- Provision of education and training throughout the Nation to increase awareness of natural hazards and to enhance the capability and skills of professionals to deal with their adverse societal impacts.
- Improvement of existing systems to communicate natural hazards and risk information, especially to public officials, policymakers, and professionals who can provide leadership for hazard mitigation.

The U.S. National Committee on the Decade for Natural Disaster Reduction will join with the committees and entities of other nations and the United Nations in carrying out the overall Decade program. The United Nations, which will have a major role in facilitating the Decade program, started their planning in March 1988 by forming a 25-member International Ad Hoc Group of Experts on the Decade. Chaired by Frank Press, this group delivered a report to the Secretary General of the United Nations on June 1, 1989, containing model programs and recommendations for an organization to implement them. The proposed organization for the United Nations consists of:

- A Board of Trustees to marshall political support and to seek funds.

- A program committee to solicit, develop, evaluate, and recommend programs to individual nations for the Decade.

- A secretariat drawn from existing UN organizations to carry out operational requirements.

The report also recommended that a trust fund be established to provide resources to assist program development, especially for developing nations. The trust fund and the funds available to each national committee or national entity would constitute the resources for the Decade program.

The challenge of the International Decade for Natural Disaster Reduction in unprecedented. If the past is an indication of what will happen in the 1990's and afterward, the United States and the world will once again face potential disasters from:

- Earthquakes, such as those that occurred in Alaska in 1964, Algeria and Italy in 1980, Chile and Mexico in 1985, and Armenia, SSR, in 1988.

- Volcanic eruptions, such as those that occurred in Mount St. Helens, Washington in 1980, Nevado del Ruiz, Columbia in 1985, and Izu-Oshima, Japan in 1986.

- Floods, such as those that occurred in Florence, Italy in 1966, Nagasaki City, Japan in 1982, and Bangladesh in 1988.

- Typhoons, cyclones, and hurricanes, such as those that occurred in Japan from typhoon Isewan in 1959, in Pakistan from a cyclone in 1970, on the eastern seaboard of the United States from hurricane Agnes in 1972, and in Jamaica and other Caribbean countries from hurricane Gilbert in 1988.

- Tornadoes, such as the Palm Sunday outbreak that struck Iowa, Illinois, Indiana, Michigan, and Wisconsin in 1965; and the super outbreak of tornadoes that struck 11 Midwestern States and Canada on April 3, 1974.

- Landslides, such as those that occurred in Alaska in 1964 in conjunction with the Prince William Sound earthquake, in Peru on the west bank of the Manatro River in 1974, in Puerto Rico in 1983, in Ecuador in 1987, and in Tajekistan, SSR in 1989.

- <u>Tsunamis</u>, such as the Showa Sanriku earthquake-tsunami that struck Japan in 1933, the Chilean earthquake-tsunami which struck Hawaii and affected the coast of almost all of the countries of the Pacific rim on May 22, 1960, and the Mindanao earthquake-tsunami that struck the Philippines on August 7, 1975.

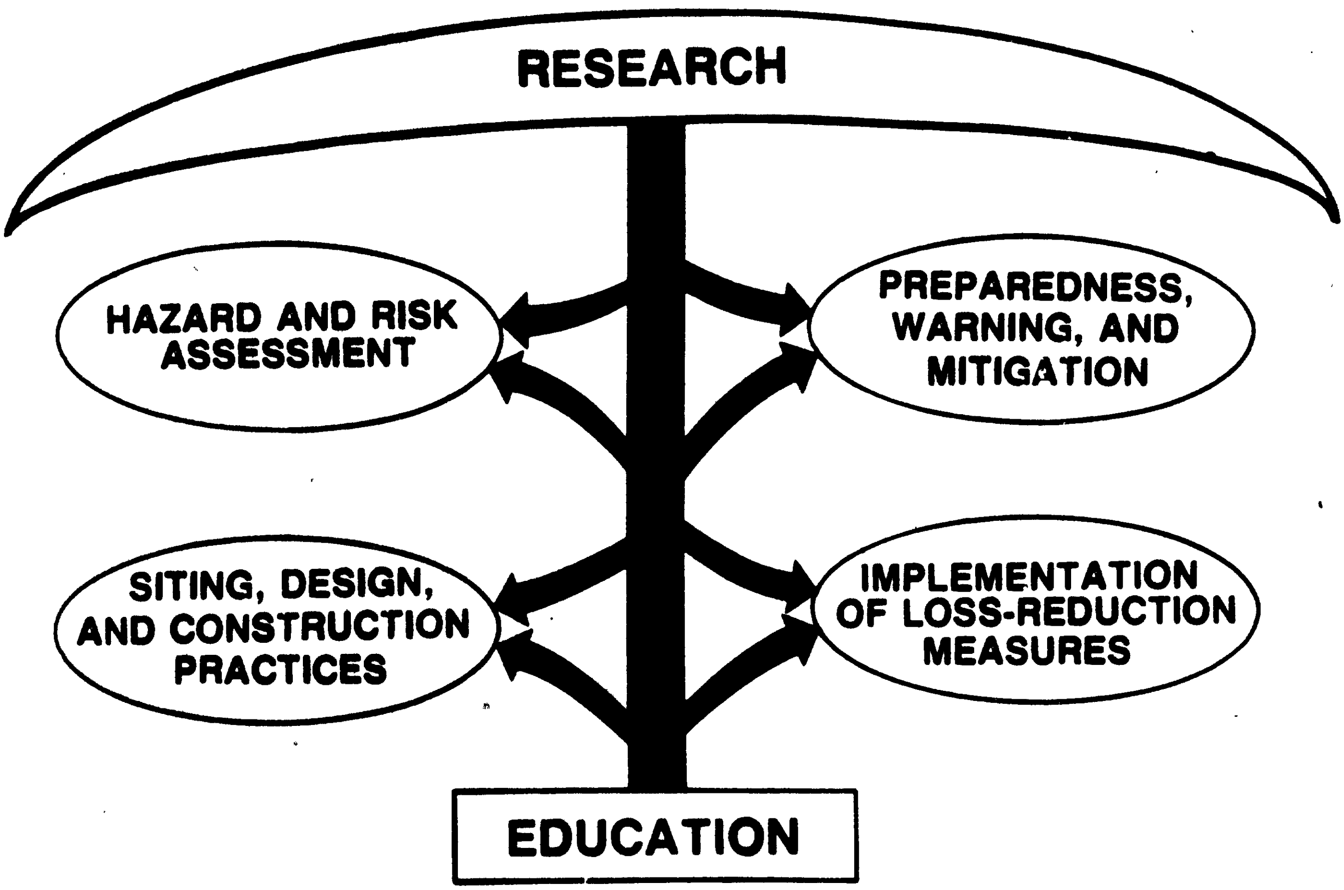
- <u>Wildfires</u> - such as those that broke out in the Great Khingan Range in northern China on May 5, 1987 and the great Yellowstone wildfires of 1988 in the Western United States.

- <u>Drought</u> - like the Dust Bowl drought on the 1930's that persisted in the Great Plains States of the United States for 10 years, and the long-term drought beginning in 1968 in the Sahel countries of West Africa.

- <u>Insect infestation</u> - such as the invasions of pilgrim locusts which have occurred often in many places in Africa.

The goal of the Decade is to keep recurrences of these natural hazards from becoming disasters. The concerted actions of all nations working together in the 1990's can make this goal a reality.

DECADE FOR NATURAL DISASTER REDUCTION



* See Explanation of Terms for definition.

U.S. National Committee for the
Decade for Natural Disaster Reduction

Explanation of Terms Used in Illustration

Hazard and risk assessment - the determination of the types of natural hazards likely to occur, their frequency, spatial extent, physical characteristics, and adverse consequences

Siting - the process whereby all relevant geological, geophysical, and engineering data are integrated into decisions concerning the location of structures or facilities

Design - the process of developing in a structure exposed to natural hazards an adequate capacity to withstand their potential physical effects

Construction practices - the process whereby professionals turn theory, experience, and construction materials into structures that will function safely during the occurrence of a natural hazard

Preparedness - detailed planning for prompt and efficient response once a natural hazard occurs

Warning - providing forecasts, alerts, and predictions for impending or potential events through technical and societal systems

Mitigation - efforts aimed at preventing loss of life, property damage, and economic losses associated with the potential occurrence of natural hazards

Implementation of loss-reduction measures - applications of knowledge to guide decisionmaking and change individual, community, and professional practices in order to reduce the exposure and potential vulnerability of people and structures to risk

Research - studies aimed at filling gaps in knowledge about all aspects of natural hazards

Education - the continuous process of informing decisionmakers, professionals, and various sectors of the public of the potential risk posed by natural hazards and the means for reducing their exposure and potential vulnerability

SEISMIC-HAZARD ASSESSMENT IN THE CENTRAL UNITED STATES

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ABSTRACT

Problems with and approaches to seismic-hazard estimation in the midcontinent of the United States are evaluated by using recent data on stress regime, crustal age and structure, and seismicity of other stable continental regions. Evaluating earthquake hazard in the central U. S. is difficult because of the lack of identifiable seismogenic faults and because of the low rate of seismic activity. Furthermore, the recurrence intervals of large earthquakes are poorly known, in part because of the short historical record that spans only a fraction of the repeat times of these quakes. The seismotectonic regime of the central U. S. is dominated by the Reelfoot rift complex and the associated New Madrid, Missouri, seismic zone. However, there are other major tectonic structures in the region such as the Nemaha ridge, the Midcontinent rift system, and the Wichita-Ouachita orogenic belt, and earthquakes that can generate damaging ground motion (approximately magnitude 5.0 or greater) have occurred in the states of Ohio, Illinois, Oklahoma, Texas, Kansas, Nebraska, Kentucky, Alabama, and Arkansas as well as Missouri. Opinions vary widely about the best way to delineate seismic source zones in such a diffuse and varied seismotectonic environment. Moreover, detailed paleoseismic or neotectonic data that could improve hazard assessments are extremely sparse in the central U. S. The Meers fault scarp in southwestern Oklahoma, with its evidence for Holocene displacement and its lack of background seismicity, highlights a new set of assessment problems. Development of site-specific probabilistic hazard curves are further hampered by the lack of strong ground-motion data and high resolution attenuation data. We address aspects of the overall seismic-hazard assessment problem for which neotectonic information provides constraints. These include a seismic source zonation for the central U. S. and estimates of maximum possible earthquakes for these zones, especially for the New Madrid region.

INTRODUCTION

There have been numerous attempts to quantify the seismic hazard in the central United States: the three most systematic, comprehensive, and recent were by the U. S. Geological Survey (Algermissen *et al.*, 1982), Lawrence Livermore National Laboratory (Bernreuter *et al.*, 1989) and the Electric Power Research Institute (EPRI, 1986). The USGS study evaluated the whole of the United States while the LLNL and EPRI studies focused on the central and eastern U. S. (east of the Rocky Mountain cordillera). All of these efforts utilized large teams of investigators and required a substantial amount of judgement as to the relative importance of the record of past seismicity versus the seismogenic potential of known geologic and tectonic structures as they are oriented within the regional stress regime. More localized central U.S. seismic-hazard studies have been conducted by Nuttli and Herrmann (1978) and Nuttli (1979).

For this report, the central United States is defined as the region bounded on the north by Canada, the south by Mexico/Gulf of Mexico, the west by the Rocky Mountain Cordillera/Rio Grande rift, and the east by the New York-Alabama aeromagnetic lineament as delineated by King and Zietz (1978). It includes the states of North and South Dakota, Nebraska, Kansas, Oklahoma, Minnesota, Iowa, Missouri, Arkansas, Louisiana, Mississippi, Michigan, Wisconsin, Illinois, Indiana, Kentucky, Ohio, and portions of West Virginia, Tennessee, Alabama, Texas, New Mexico, Colorado, Wyoming, and Montana.

Seismic-hazard estimation includes a number of elements. Where active and capable faults are known and mappable as in the western U. S., the hazard will depend on the seismic potential, that is, the activity rate and the largest earthquakes that the fault(s) can sustain. In the central and eastern U. S., active faults are rarely identified and additional, more indirect steps are necessary. The "classical" approach to hazard assessment for the central United States involves: (1) delineating seismic source zones based on either seismicity, tectonics, or a combination of both; (2) assigning a frequency-magnitude recurrence relation and a maximum possible earthquake for each source zone; (3) developing regional anelastic attenuation relations and applying them to sites within the study area; (4) producing a hazard curve by incorporating contributions from all source zones at a specific site. For an individual site, the hazard curve estimates the probability of exceeding a particular ground motion parameter, usually peak or sustained ground acceleration; an example is given in Figure 1. The usual style of presentation for a region is a contour map showing the level of ground motion that will not be exceeded with a specified time period (e.g., Algermissen *et al.*, 1982).

For this study, as part of a symposium on applying neotectonics to earthquake risk evaluation, we will emphasize the problems of identifying seismic source zones and assigning source parameters to these zones; this is where neotectonic information is incorporated into the hazard evaluation process. We do not address the equally important questions of proper probabilistic and statistical modeling of ground motion .

As with seismic hazard, the seismicity and tectonics of the central United States have been the subjects of extensive previous investigations (e.g., Nuttli and Herrmann, 1978; Nuttli, 1979; Van Schmus *et al.*, 1987; Bickford *et al.*, 1986; Hatcher *et al.*, 1987). A detailed and comprehensive reexamination is not included here; rather, our objective is to define the seismicity and large-scale tectonic features in a general sense in order to characterize the problems in seismic-hazard assessments in the region. In our view, the single most difficult problem is estimating the "seismic potential" of a zone or a crustal structure. Aside from the question of properly delineating the zone, this seismic potential has two components: an estimate of the maximum possible earthquake and an estimate of the frequency of occurrence of moderate-to-large events ($m > 5$). Both components are essential for hazard estimation, yet quantitative constraints for these parameters are sparse. For the central United States where the historical record of seismicity is short, where the character of the crust at seismogenic depths is obscure, and where the earthquake potential of most of the recognized crustal structures is unknown, assessing the seismic potential is based more on judgement than knowledge. In the following we present a brief overview of the region in terms of its crustal composition, tectonics, stress regime, and seismicity. Finally, we return to the question of seismic "judgement" as part of an exercise of seismic zonation of the central United States.

THE CRUST OF THE CENTRAL U.S.

How can the crust of this region be usefully characterized for assessing seismic potential? To begin, there is little doubt that earthquakes are generated in the upper crust, above the brittle-ductile transition, 20-30 km deep. However, in the central U. S. crystalline basement is concealed beneath a veneer of Paleozoic sedimentary rocks. Virtually all large earthquakes, which have sufficient data to closely constrain hypocentral depth, occur within the igneous and metamorphic rocks of the upper crust, although some faulting as revealed by aftershocks does extend up into Paleozoic strata. Moreover, there is no documented case of surface fault rupture accompanying any earthquake in the central U. S. (The Meers fault in southwest Oklahoma is a remarkable exception to this rule for a prehistoric earthquake and will be discussed later in this review.)

The crystalline crust of the central United States is wholly Precambrian in age, with the possible exception of the southern coastal block (e.g., Hoffman, 1988). Classically, this region is divided into Canadian shield and interior platform, which together comprise a collage of at least five cratonic elements (Figure 2), the products of major Precambrian orogenic episodes, ranging in age from Superior craton nucleation in the Archean (3.8 to 2.5 b.y.) to the middle Proterozoic Grenville orogeny (1.1 b.y.) (Hoffman, 1988). Most age determinations of the crust are from drill-hole samples; the principal outcrops of Precambrian rocks (the Superior craton in Minnesota, the Ozark dome in Missouri, the Llano uplift and Van Horn/Franklin Mountains of Texas, and the Black Hills uplift of South Dakota) are few and isolated.

This representation of a Precambrian central U. S. crust that grew to the south and east via lateral accretion during successively younger orogenies is derived from data only recently available. U-Pb age dating on zircon concentrates from drill cuttings (Van Schmus *et al.*, 1987) is perhaps the most useful technique for applying these data to problems of midcontinent crustal evolution. Reliable dates are obtained from small samples, which—unlike for Rb-Sr or K-Ar dating—can tolerate some minor weathering and/or alteration. A comprehensive evolutionary framework for our study region is developing rapidly.

TECTONICS OF THE CENTRAL UNITED STATES

North of the Paleozoic Ouachita system, Phanerozoic tectonics had minimal effect on the crust of the central U. S. The interior platform was consolidated into a vast composite craton by about 1,300 m.y. This is not to say, however, that tectonic processes ceased to operate in the region. The most prominent example of this is the Midcontinent rift system (Chase and Gilmer, 1973; Van Schmus and Hinze, 1985) (see Figure 3). It has the strongest gravity signature in the central U. S., consisting of a belt of sharply defined linear, positive Bouguer gravity anomalies extending from Michigan to Kansas, with central highs of +60 mgal flanked by lows of -100 mgal. Rocks in the rift system are contemporaneous with those of the Grenville province to the east, raising the possibility the two are genetically related. Although the origin of the Grenville province is poorly understood, it may represent an ancient continental collision zone that formed the Midcontinent rift system behind the suture front in response to extensional forces. A present-day analogue to this is the Baikal rift zone of central Asia that lies well north of the India-Asia collision zone.

Figure 3 depicts a number of other primary tectonic features in the central U. S. and categorizes them according to whether they are expressed at the surface (geologically defined) or in the subsurface (geophysically defined). We preferentially emphasized rifts and sutures in this figure because a recent study (Coppersmith *et al.*, 1987; Johnston, 1989) identifies these structures as important features that localize seismicity in the stable interiors of continents.

The Paleozoic Ouachita thrust and fold belt is the major Phanerozoic suture traversing the study area. It is generally interpreted as a continuation of the Appalachian system (Hatcher, *et al.*, 1987), but the connections are concealed beneath the Gulf Coastal Plain sediments of Alabama. The Ouachita belt represents the southern boundary of Precambrian North America; it juxtaposes Proterozoic cratonic crust to the north with crust of unknown age and uncertain character (continental or transitional oceanic) to the south (Viele, 1979).

Another possible but less-clear continental suture is the New York-Alabama lineament, the eastern boundary of the study area. The crustal structure that produces this aeromagnetic lineament is within Grenville-age crust beneath the Appalachian decollement. It has been interpreted as a major strike-slip fault associated with continental collision (King and

Zietz, 1978); alternatively, it may demark the suture between the Grenville crust of North America and an accreted terrane named the Clingman block by Johnston *et al.* (1985) or the Bristol block by Hatcher *et al.* (1987).

Three major failed continental rift complexes or aulacogens intersect the Ouachita belt at high angles: the Delaware aulacogen of west Texas, the southern Oklahoma aulacogen, and the Reelfoot rift complex. All are Eocambrian (575-700 m.y.) in age (e.g., Gordon, 1988) but at least the Reelfoot rift, and probably the others, experienced additional extension and intrusion during early Mesozoic-to-Cretaceous time (Braile *et al.*, 1984). The similar ages for the formation of these rifts suggests that they formed as perhaps failed arms of triple junctions (the Reelfoot rift may represent more than one) during an episode of late Precambrian continental break-up that predated the Ouachita-Appalachian orogeny.

Other smaller crustal features or their geophysical expressions might be included in Figure 3 that perhaps could be relevant to earthquake occurrence in stable continental settings. For example, basement uplifts and basins, gravity and magnetic highs and gradients, mafic and felsic plutons, shallow crustal grabens, and faults with a wide range of dimensions have been considered in the literature. A cause-and-effect relationship between these smaller scale features and seismicity remains tenuous and is therefore not promoted here. Local stress concentrations arising from these crustal inhomogeneities may produce moderate-size earthquakes (up to magnitude 5.0-5.5), but we contend that the larger, damaging events will be associated with the major crustal features, mainly rifts, shown in Figure 3. In fact, in stable continental regions worldwide, earthquakes exceeding moment magnitude 6.0 are exceedingly rare except in crust that has experienced extensive rifting since the Mesozoic (Coppersmith, *et al.*, 1987; Johnston, 1989).

THE STRESS REGIME OF THE CENTRAL UNITED STATES

The stress regime—or more accurately the orientation of the horizontal principal stresses that has the greatest deviation from lithostatic stress—has of the contiguous United States been estimated by Zoback and Zoback (1980; 1989) using earthquake focal mechanisms, in-situ stress measurements, and the orientation of stress-sensitive geologic features. The principal differences between the 1980 and 1989 studies are that in the more recent study, Zoback and Zoback deleted stress orientation estimates based on overcoring data or geologic features older than Miocene and included recent wellbore-breakout data. These changes resulted in significant differences in the 1980 and 1989 stress-regime maps in the eastern and western United States; however, the stress regime for the central U. S. remained unchanged. This suggests that the stress regime in the central U. S. is remarkably uniform with the direction of maximum horizontal compression trending from northeast to east-northeast as the region is traversed from northeast to southwest (Figure 4).

There are some relatively minor exceptions to simple stress state described above. An extensional stress province is present in the extreme southwest corner of the study area in Texas and New Mexico, possibly representing a transitional zone between the active extensional tectonics of the Rio Grande rift directly to the west and the stable platform of the central plains. The stress orientation for the basement crust of the southern coastal block (Figure 2) beneath the thick deposits of coastal plain sediments is unknown. And, of course, the magnitude of the horizontal stress deviation from lithostatic conditions at hypocentral depths is not known anywhere in the study region.

This picture of a uniform deviatoric stress state for the central U. S. has several important implications for seismic-hazard estimation. Most, if not all, earthquakes occur in a brittle upper crust which was assembled and incorporated into continental North America more than one billion years ago. The borders of this region, at all but the northern margin, experienced additional significant tectonism throughout the Paleozoic and into the Cenozoic. Evidence of this Phanerozoic (and the older Proterozoic) activity remains in the form of the primary tectonic features of Figure 3. At present, and probably since the Miocene, this ancient, scarred crust is being subjected to a compressive, regionally uniform stress regime that originates from plate margin interactions remote from the region itself. Our task now is to use this understanding of stress regime and crustal structure to explain the observed seismicity of the central U. S. and, ultimately, to derive useful estimates of the pattern and severity of future seismic activity.

THE SEISMICITY OF THE CENTRAL UNITED STATES

The seismicity of the central United States is depicted in Figures 5 and 6. Although the orientation of the horizontal deviatoric component of the stress regime in the central U. S. seems to be very uniform, the distribution of earthquakes decidedly is not. Whether one considers total known seismicity ($m_b \geq 3.5$, Figure 5) or only the larger events ($m_b \geq 5.0$, Figure 6), nonrandomness is obvious. While it is likely that this two-to-three century 'snapshot' of seismicity is inadequate to show the complete, detailed pattern, we argue that it is sufficient to establish an inherent high degree of clustering. It follows that physical reasons must exist for the observed clustering of seismic energy release in the central U. S.

The distribution of earthquakes shows little correlation with provinces of similar crustal age (Figure 2). However, if only larger events are considered (see Table 1), there is a good correlation with primary tectonic structures (Figures 3 and 6). Thus it is probable that the type of feature, its geologic age, and its orientation within the prevailing contemporary regional stress regime are all important contributing factors to earthquake generation in stable continental interiors.

The most pronounced cluster of activity (Figures 5 and 6) centers on the confluence of the Mississippi and Ohio Rivers at the head of the Mississippi embayment and is clearly spatially associated with the Reelfoot rift complex of Figure 3. No earthquake exceeding magnitude 6 has occurred in the central United States outside of this zone since settlement of the region by Europeans. (The 1931 West Texas event—moment magnitude 6.3 (Doser, 1987)—occurred in a zone of active faulting associated with the Rio Grande rift and thus has a closer affinity to western U. S. tectonics than to the stable midcontinent.)

The great New Madrid earthquakes of the winter of 1811-1812, as well as the current seismicity of the zone (Figure 8), have been extensively discussed in the literature; we need not repeat those discussions here (see Johnston, 1982, for an overview). Clearly, from Figures 3, 5, and 6 and Table 1, the New Madrid zone, including its probable northward extensions, completely dominates central United States seismicity. In fact, it has the highest seismic moment release rate of any seismic zone in a stable continent region in the world (Coppersmith *et al.*, 1987; Johnston, 1989). Why is the New Madrid region unique considering that other continental interiors contain numerous primary tectonic structures and are thought to be subject to fairly uniform regional stress regimes?

The answer to the preceeding question is not straightforward and requires a degree of speculation or seismic judgement. One possible answer is that with a much longer record of seismicity, other crustal structures in the central U. S. or in other stable continental regions might be the loci of large earthquakes, i.e., the assumption of a temporally stochastic pattern of earthquake occurrence is invalid. While we cannot exclude this possibility, we do not favor it and cite the highly stochastic character of the longer seismicity record of China (e.g., McGuire, 1979).

We propose four factors that, combined, make the Reelfoot rift complex especially, perhaps uniquely, susceptible to a high rate of seismicity and the generation of major earthquakes. First, as previously mentioned, it is a major, throughgoing crustal structure. This may be essential to localizing a high strain rate (Anderson, 1986).

Second, the rift is oriented ideally with respect to the regional stress regime (Figure 4) for the ratio of shear-to-normal stress to be maximized on preexisting fault systems. (Note that its active west-northwest segment is a good left-lateral strike-slip representation of the auxiliary nodal plane for the right-lateral strike-slip mechanism of the southwest-trending axial zone.) Other major structures of Figure 3 tend to strike perpendicular or parallel to the regional stress, yielding a less-than-optimum ratio of shear-to-normal stress.

Third, the major Mesozoic-Cenozoic reactivation of the Reelfoot rift is tectonically relatively young, and its crustal disruption has not had time to heal. This may be the factor that explains the aseismicity of the middle Proterozoic midcontinent rift system.

Fourth, and most speculative, is the observation that the Reelfoot rift complex is saturated with water from the largest of the North American drainage systems. It is a "wet" seismogenic structure and some evidence suggests that this may be an important contributing factor for intraplate earthquake generation (Nava and Johnston, 1984; Costain *et al.*, 1987).

CHARACTERIZATION OF INTRAPLATE SEISMIC SOURCE ZONES

To provide a seismic-hazard evaluation for the central United States, we must confront the problem of defining seismic source zones in a region virtually devoid of identifiable active faulting. We propose as a useful approach a classification of seismic source zones that includes information on the degree of knowledge available to define the zone.

In regions such as the central U.S. that lack identified active faults, the concept of a "seismic source zone" is in itself an admission of lack of knowledge. Abundant seismological evidence indicates that shallow non-volcanic earthquakes are satisfactorily modeled as shear failures on planar or at least tabular features we call faults. A seismic source zone, then, represents a geographic region which is judged to contain at least one and perhaps a collection of faults capable of generating earthquakes. Seismic parameters—principally the frequency-magnitude relation and maximum magnitude earthquake—are assumed to be homogeneous throughout the zone. Along plate boundaries and throughout most of the western United States, seismic source zones can be restricted rather confidently to mapped fault zones, although the presence of unrecognized source zones remains (e.g., the Coalinga earthquake for which the causative fault was concealed by an anticline ridge structure of Pliocene and younger age (Clark *et al.*, 1983)).

In the central United States seismic source zones are generally large, a reflection of large uncertainty in their definition. Moreover, in an exercise in which 13 'experts' were requested by Lawrence Livermore National Laboratory to independently zone the central and eastern U.S., the divergence of the resulting maps was startling, as was the range of criteria that the experts used to delineate the source zones (Bernreuter *et al.*, 1989; Figure 3 in Anderson, 1986). Most weight was given to historical seismicity patterns, with tectonic structure and orientation to the regional stress regime also ranking high in importance, but the emphasis and interpretation of each expert varied greatly.

The classification of intraplate seismic source zones (ISSZs) proposed by Johnston (1987) enables one to define seismic source zones in a systematic manner. This is useful because it helps characterize seismic hazard in these regions while incorporating the current level of uncertainty in the definition of the source zones. As used here the term 'intraplate' excludes all features on which plate contact seismicity occurs or zones directly associated with plate margins in which it is clear that relative plate motions are accommodated, even though slip vectors may not be oriented subparallel to the relative plate motion vector. (Examples of such interplate seismic source zones include actual plate boundaries, subsidiary faults in the San Andreas system, and outer rise or overriding wedge earthquakes in subduction zones.) The distinction between interplate and intraplate is most difficult in regions such as south central Asia or portions of western North America where plate motion is accommodated over a broad zone. Such distributed plate boundaries are commonly included in the intraplate category.

The intraplate designation can be further subdivided according to whether a region is subject to significant Mesozoic/Cenozoic tectonic activity. If this is absent, we term the region 'stable continental interior' (SCI). In SCI regions active surface faulting is rare, and consequently, precision and confidence in delineating ISSZs is limited. Our study area, the central U. S., is an SCI region.

The proposed classification for continental intraplate seismic source zones is given in Table 2. All intraplate regions are assigned to one of six categories, depending on known (or unknown) tectonic, geologic, and seismological characteristics. Categories 1 through 6 (Table 2) imply a steplike transition from abundant data that clearly define an ISSZ (Category 1 and 2) to a virtual lack of data for background zones (Category 6). In reality, the categories are gradational and, as new data are acquired and knowledge improves, seismic sources can be redefined into new, better constrained ISSZs. One of the primary objectives of seismic-hazard research is to upgrade category 3-6 zones—where most continental intraplate ISSZs now would be classified—into category 1 or 2.

SEISMIC SOURCE ZONATION OF THE CENTRAL UNITED STATES

To zone the central U. S. for hazard analysis, we must (1) delineate individual seismic source zones, (2) assign a maximum 'credible' earthquake to each zone, (3) estimate the rate of seismic activity for each zone, and (4) determine the anelastic attenuation from each zone to sites of interest. Estimating the seismic activity and attenuation are beyond the scope of this study, but we will examine how to approach tasks (1) and (2) for the central United States.

The previously cited study of Coppersmith *et al.* (1987; see also Coppersmith and Youngs, 1989) that assessed the worldwide occurrence of seismicity in stable continental interiors (SCI) provides a comprehensive data base that can guide source zone definition and maximum earthquake selection in the central U. S. To counter the probability that the observational record is neither sufficiently long nor complete, Coppersmith *et al.* compiled data from magnitude 5.0 or greater earthquakes from all stable continental regions. They found fewer than 20 known events of magnitude 7.0 or greater in these regions, and the level of seismic activity varies greatly on a continent-size scale. Most large events have been preceded by known historical or instrumental seismicity and have occurred in crust of Paleozoic rather than Precambrian age.

Other findings from the SCI study are applicable to seismic source zonation in the central U.S. They include (1) a compressive horizontal deviatoric stress regime dominates in SCI regions worldwide, producing mostly thrust and strike-slip earthquakes; (2) from a total data set of over 500 events, $m_b \geq 5.0$ earthquakes are strongly associated with continental rifts of Mesozoic age and younger, and continental margins or suture zones; (3) the rifted-crust association is even stronger for large earthquakes—those that exceed magnitude 7 occur exclusively in zones of Mesozoic/Cenozoic rifting, i.e., passive continental margins (successful rifts) or intracontinental (failed) rifts; (4) surface fault rupture is extremely rare and has been confidently documented in only two percent of the SCI data set (eight occurrences).

Given the information compiled in Coppersmith *et al.* (1987), how should one proceed with seismic zonation in SCI regions? The study imposes a strong constraint on source zone delineation by limiting large (M > 6.9) SCI earthquakes to a few possible tectonic settings. Since a seismic zone must have the same maximum earthquake assigned to the entire zone, boundaries should be based on mapped or geophysically-inferred structural boundaries, principally of Mesozoic or younger rifts.

The problem of defining the seismic source zone for maximum New Madrid earthquakes was addressed by Johnston and Nava (1985) in their analysis of recurrence probabilities of such events (Figure 7). They concluded that, although the crustal elastic strain storage volume for the 1811-12 earthquake sequence must far exceed the Reelfoot rift boundaries of Hildenbrand *et al.* (1982), major New Madrid earthquakes will be restricted to the principal fault segments within the boundaries of the rift. These segments are delineated by the concentrated pattern of instrumental earthquake epicenters shown in Figure 8. We conclude that the principal seismicity segments of the New Madrid seismic zone must be separately zoned from the rest of the Reelfoot rift complex because it has a different (higher) maximum earthquake potential.

The study of Coppersmith *et al.* (1987) offers useful guidance in restricting the major $M \geq 7$ earthquakes of SCI regions to a few locales, but what of the significant hazard contributed by damaging, moderate-magnitude events? Background seismicity (e.g., Figure 5) is an unreliable, even misleading, guide to where such events may occur—witness the 1980 M5.2 Sharpsburg, Kentucky, earthquake, the 1982 M5.6 New Brunswick earthquake, or the 1986 M5.0 earthquake near Cleveland, Ohio. We conclude that while major earthquakes can be localized to certain types of primary tectonic structures, one must allow for the occurrence of magnitude 5.0-5.5 events virtually anywhere in the central U. S.

Having examined some of the issues involved in seismic source zoning and maximum earthquake designation, we now proceed to zone the Central U.S. In Figure 9 we subdivide the central U. S. into seismic source zones (SSZ) that are labeled according to the type of data used to define the zone (see Table 2). Two requirements controlled the selection of the SSZs in Figure 9. The most important criterion is that the maximum earthquake must be allowed to occur anywhere within the boundaries of the identified source zone. Because fault dimensions of even the largest midplate earthquakes will likely not exceed 100 km (Nuttli, 1983), the SSZs of Figure 9 obviously do not represent monolithic seismogenic structures; rather they are regions within which structures have similar seismogenic potential. In applying this criterion, we emphasize the maximum earthquake component of seismic potential rather than seismic activity rate.

This first SSZ selection requirement leads directly to the second: boundaries of identified SSZs should be based primarily on the known or inferred extent of primary tectonic features (Figure 3). This is a significant departure from the past practice of defining seismic source zones based on the record of historical seismicity.

The maximum earthquake estimated for each SSZ in Figure 9 is based on both the largest known earthquake for the zone and on the earthquake record of similar SSZs in global data base of Coppersmith *et al.* (1987). Note that of all central U. S. seismic source zones, only the Reelfoot rift SSZ has experienced our estimated maximum earthquake in historic times.

We have defined fewer seismic source zones in Figure 9 than some previous studies (e.g., Nuttli and Herrmann, 1978; Bernreuter *et al.*, 1989). This is because we recognize the possibility of a moderately large earthquake (m_b 5.0-5.5) over a very broad 'background' SSZ (category 6, Table 2) based on the worldwide study (Coppersmith *et al.*, 1987) that shows that many such events in SCI environments cannot be associated with primary tectonic structures. Thus our background SSZ combines many seismic source zones that previously had been treated separately (e.g., the Ozark uplift, the Colorado lineament, various intra-cratonic basins or uplifts). Past seismic activity and the orientation to the regional stress field are additional contributing factors that we considered.

The Reelfoot Rift/New Madrid SSZ

The Reelfoot rift complex is subdivided into two separate SSZs (Figure 10), a 'seismic' SSZ (Zone A) and a 'seismotectonic' SSZ (Zone B) (see Table 2). Zone A is delineated on the basis of the linear trends of numerous small earthquakes epicenters (Figure 8). The linearity of the pattern suggests that this zone is actually composed of several seismogenic fault segments; these probably last ruptured in their entirety in the great earthquake sequence of 1811-1812. Moreover, seismic-reflection profiles have actually imaged an upper crust 'disturbed zone' that is coincident with the southwest arm of Zone A (e.g., Crone *et al.*, 1985).

Zone B is defined by the geophysically-inferred limits of the Reelfoot rift complex. Its borders are the margins of the rift as defined by magnetic and gravity data by Hildenbrand *et al.* (1982) to the south, and by Braile *et al.* (1984) to the north. The geophysical signature of the Reelfoot lobe is much clearer than the Saint Louis and Wabash Valley lobes to the north, but the geophysical data and seismic activity are significant enough that these northern branches should not be ignored in hazard zonations.

The east-west Rough Creek graben zone is included as a fourth lobe by Braile *et al.* (1984). It is clearly a rift-type structure, but we classify it as a "tectonic" SSZ (category 5, Table 2) because it has no associated significant seismic activity. The lack of seismicity is probably related to the fact that its orientation is nearly parallel to the prevailing regional horizontal principal stress. We consider the probability of significant earthquakes ($m_b \geq 5.5$) in this zone to be much lower than the rest of Zone B; therefore we remove it from Zone B on the map in Figures 9 and 10.

We assign as the southern boundary of Zone B the inferred extension of the Ouachita foldbelt beneath the Mississippi embayment. This choice of boundary is not based on hard data. It is unclear that the rift structure of Hildenbrand *et al.* (1982) extends to the foldbelt, but there is no evidence that the rift extends south of the Ouachita belt. Therefore, it seems a logical place to truncate Zone B.

In terms of perceived seismic hazard, the distinction between Zone A and Zone B is important: both the maximum possible earthquake and the seismic activity rate differ substantially for the two subzones. We believe that a great earthquake of $m_b \geq 7.0$,

$M_s \geq 8.0$ would be restricted to Zone A. A possible, although admittedly qualitative, explanation for this is that the crustal rock of stable continental interiors is normally strong enough to inhibit or confine coseismic rupture propagation; only within the faulted and weakened segments of Zone A can rupture propagate to sufficient dimensions to produce great earthquakes. Thus we regard the New Madrid Zone A as a special case that is virtually unique in North America with the possible exception of portions of the Saint Lawrence rift valley.

Even though the boundaries of Zone B are fairly well defined by geophysical methods, its maximum magnitude earthquake is difficult to estimate with any degree of confidence. On the basis of the Coppersmith *et al.* (1987) study, we assign an m_b 6.5 as the maximum probable event. Low magnitude 6 events have occurred in continental rift environments currently under compression in Europe (Rhine graben), India (Cambay and Godavari grabens), North America (St. Lawrence rift), Australia (Adelaide geosyncline, Fitzroy trough), and Africa (Sirte grabens). Events larger than m_b 6.5 have occurred in the St. Lawrence and Sirte regions, but we consider these analogous to New Madrid Zone A events. The assigned maximum earthquake of m_b 6.5 has not been experienced in historic times in Zone B, but the occurrence of similar magnitude shocks in tectonically similar rift settings worldwide suggests such an event is possible in Zone B.

On the basis of the historical seismicity (Figure 5) and instrumental seismicity (Figure 8), significant earthquakes are more likely in Zone B north of latitude 35.5. One could argue for separate zones, but we feel this relies too heavily on the short historical record. Nevertheless, the relatively aseismic nature of Reelfoot rift south of Marked Tree, Arkansas is an enigma.

Epilogue: The Meers Fault

The Meers fault, located in the Oklahoma aulacogen (Figure 3), represents a probable prehistoric exception to the domination of central U. S. seismicity by the New Madrid zone. Strong geologic evidence now indicates a magnitude 7+ earthquake on this fault within the past 1,100 to 1,400 years (Luza *et al.*, 1987; Ramelli *et al.*, 1987; Madole, 1988). If the fault's dip is subvertical at hypocentral depths, its orientation is favorable for left-lateral strike-slip movement, which is the observed dominant slip component. It has been virtually aseismic throughout the historical past.

Thus the Meers fault, with its prominent surface scarp, represents a western-style (e.g., surface rupture), active fault within the central U. S. stable interior. It is already forcing a reexamination of seismic zonation practices, which, in the past, have relied heavily on historical seismicity, because it violates the assumption of stationarity of seismicity on which much seismic-hazard analysis is based. It is an important reminder that we must continually question our assumptions and strive to improve our understanding of the tectonics underlying the seismogenic process in the central United States.

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TABLE 1

Central United States Earthquakes m ≥ 5.0

DATE	LOCATION/LOCALE	MAGNITUDE	MMI_0	REFERENCE
		TWENTIETH CENTURY (1901-1987)		
1987 06 10	38.713/87.954 [SE Illinois]	5.1 m_{bLg}	VI	Taylor *et al.*, 1989
1986 01 31	41.642/81.109 [NE Ohio]	5.0 m_b	VI	Nicholson *et al.*, 1987
1980 07 27	38.18 /83.94 [NE Kentucky]	5.2 m_b	VII	Herrmann *et al.*, 1982
1968 11 09	37.96 /88.46 [SE Illinois]	5.5 m_{bLg}	VII	Gordon *et al.*, 1970
1952 04 09	35.525/97.850 [Central OK]	5.5 M_S	VII	Gordon, 1988
1937 03 09	40.470/84.280 [W. Ohio]	5.0 m_b	VII	Nuttli & Brill, 1981
1931 08 16	30.69/104.57 [SW Texas]	6.3 M_S	VIII	Doser, 1987
1925 07 30	35.4/101.3 [N. Texas]	5.2 M	VI	Davis *et al.*, 1989
1917 04 09	38.10/90.20 [E. Missouri]	5.0 m_b	VI	Nuttli & Brill, 1981
1916 10 18	33.5/86.2 [N. Alabama]	5.3 m_b	VII	Steigert, 1984
1909 05 26	42.0 /89.0 [N. Illinois]	5.0 m_b	VII	Nuttli & Brill, 1981
1909 05 16	50.0 /104.0 [U. S.-CAN. Border]	5.5 m_b	VI	Horner & Hasegawa, 1978
1905 08 22	36.8/89.6 [SE Missouri]	5.1 m_b	VI-VII	EPRI catalog, 1986
		NINETEENTH CENTURY (1801-1900)		
1895 10 31	37.0 /89.4 [SE Missouri]	6.2 m_b	IX	Nuttli & Brill, 1981
1891 09 27	38.25/88.50 [SE Illinois]	5.5 m_{bLg}	VII	Street, 1980
1882 10 22	35.9 /95.1 [E. Oklahoma]	5.5 m_b	VIII	Nuttli & Brill, 1981
1877 11 15	41.0 /97.0 [E. Nebraska]	5.0 m_b	VII	Nuttli & Brill, 1981
1875 06 18	40.2 /84.0 [W. Ohio]	5.2 m_b	VII	EPRI Catalog, 1986
1867 04 24	39.17/96.30 [NE Kansas]	5.1 m_b	VII-VIII	Dubois & Wilson, 1978
1865 08 17	36.5 /89.5 [SE Missouri]	5.3 m_b	VII	Nuttli & Brill, 1981
1857 10 08	38.7 /89.2 [SW Illinois]	5.1 m_b	VII	EPRI Catalog, 1986
1843 01 05	35.5 /90.5 [NE Arkansas]	6.0 m_b	VIII	Nuttli & Brill, 1981
1838 06 09	38.5 /89.0 [S. Central IL]	5.0 m_{bLg}	VI	EPRI Catalog, 1986
1812 02 07	36.5 /89.6 [SE Missouri]	7.4 m_b/8.8 M_S	XII	Nuttli, 1983
1812 01 23	36.3 /89.6 [SE Missouri]	7.1 m_b/8.4 m_S	X-XI	Nuttli, 1983
1811 12 16	36.0 /90.0 [NE Arkansas]	7.0 m_b/8.3 m_S	—	Street & Nuttli, 1984
1811 12 16	36.0 /90.0 [NE Arkansas]	7.2 m_b/8.5 m_S	XI	Nuttli, 1983

TABLE 2

CONTINENTAL INTRAPLATE SEISMIC SOURCE ZONES

CATEGORY		NAME	DESCRIPTION
1	[A]	ASEISMIC	An ISSZ within which there is no known significant seismic activity. Moreover, the region is understood well enough geologically and geophysically to exclude with high confidence the possibility future significant earthquakes.
2	[SG]	SEISMOGENIC	A specific geologic entity (usually a fault) that can be defined geologically or geophysically and, on which, earthquakes are known to have occurred, or there is evidence of prehistoric earthquakes.
3	[ST]	SEISMOTECTONIC	A clearly defined tectonic feature such as a fault zone, rift, suture, intrusion, etc. with which seismicity is spatially associated, but a clear association with a specific fault or faults is lacking.
4	[S]	SEISMIC	A region where seismicity is "enhanced over background" and spatial clustering is evident, but data are insufficient to associate the activity with seismogenic or seismotectonic crustal structures.
5	[T]	TECTONIC	Geologic or geophysical data resolve a crustal feature that elsewhere is known to be associated with earthquakes, but in this case no instrumental, historical, or paleoseismic data exist that suggest the feature has experienced significant seismicity.
6	[B]	BACKGROUND	A region with no known significant seismicity or known geological/tectonic features capable of significant earthquakes, but the data are too poor to exclude their existence with confidence.

FIGURE CAPTIONS

Figure 1. Example of a site-specific seismic-hazard curve showing ground motion (acceleration) plotted against an annual probability of exceedance. This particular curve is for a nuclear power site in Illinois. [after Bernreuter *et al.*, 1989]

Figure 2. Age subdivisions of the crust of the central United States. The ages apply to the crystalline basement that is covered by Paleozoic strata over most of the region north of the Ouachita system and are derived mainly from U-Pb zircon dates from drillhole samples.

Figure 3. Principal tectonic features of the central United States. Rift zones and sutures are emphasized over shallow crustal or epeirogenic features. Structures identified primarily by geophysical methods (subsurface) are hatchured; those with clear geological expression (surface) are blank.

Figure 4. The regional stress regime (horizontal, greatest deviatoric component) for the central U. S. as determined by Zoback and Zoback (1989). Heavy dashed lines separate stress provinces (named); lighter dashed-dotted lines show physiographic boundaries.

Figure 5. Seismicity of the central United States. The source is the EPRI catalog (1986). A plot from the other major catalog for the central U. S. (Nuttli and Brill, 1981) would exhibit a similar pattern but would differ considerably in detail.

Figure 6. Known earthquakes for the central United States of magnitude 5.0 or greater. Compiled from the sources listed in Table 2. Another 13 events, not shown in this figure, would fall between magnitudes 4.7 and 5.1 in some sources but for this study were judged to be less than 5.0 on the m_b or m_{bl_g} magnitude scales.

Figure 7. Instrumental seismicity of the New Madrid seismic zone. Data are from the Central Mississippi Valley Earthquake Bulletin published by Saint Louis University. Magnitudes range from low magnitude 1 to magnitude 5.0; depths range from 23 km to shallow (5.0 km, restricted).

Figure 8. The frequency-magnitude relation for the New Madrid seismic zone (modified from Johnston and Nava, 1985). The data base combines annualized historical seismicity (m_b 3.8-6.2) from Nuttli and Brill (1981) and the instrumental seismicity of Figure 8. Recurrence for events of magnitude exceeding m_b 6.2 is extrapolated.

Figure 9. Seismic source zones for the central United States. The criteria for defining each zone is indicated (see categories of Table 2). The estimated maximum earthquake and

zone boundaries are derived from arguments presented in the text. See Figure 10 for detail on the Reelfoot rift/New Madrid seismic zone. Abbreviations: T, tectonic; ST, seismotectonic; S, seismic; B, background; SG, seismogenic; A, aseismic.

Figure 10. Subdivision of the Reelfoot rift complex into a "seismic" source zone (SSZ), Zone A, and a "seismotectonic" SSZ, Zone B. The two zones are separated on the basis of the type of data used for their definition and the estimated maximum possible earthquake.

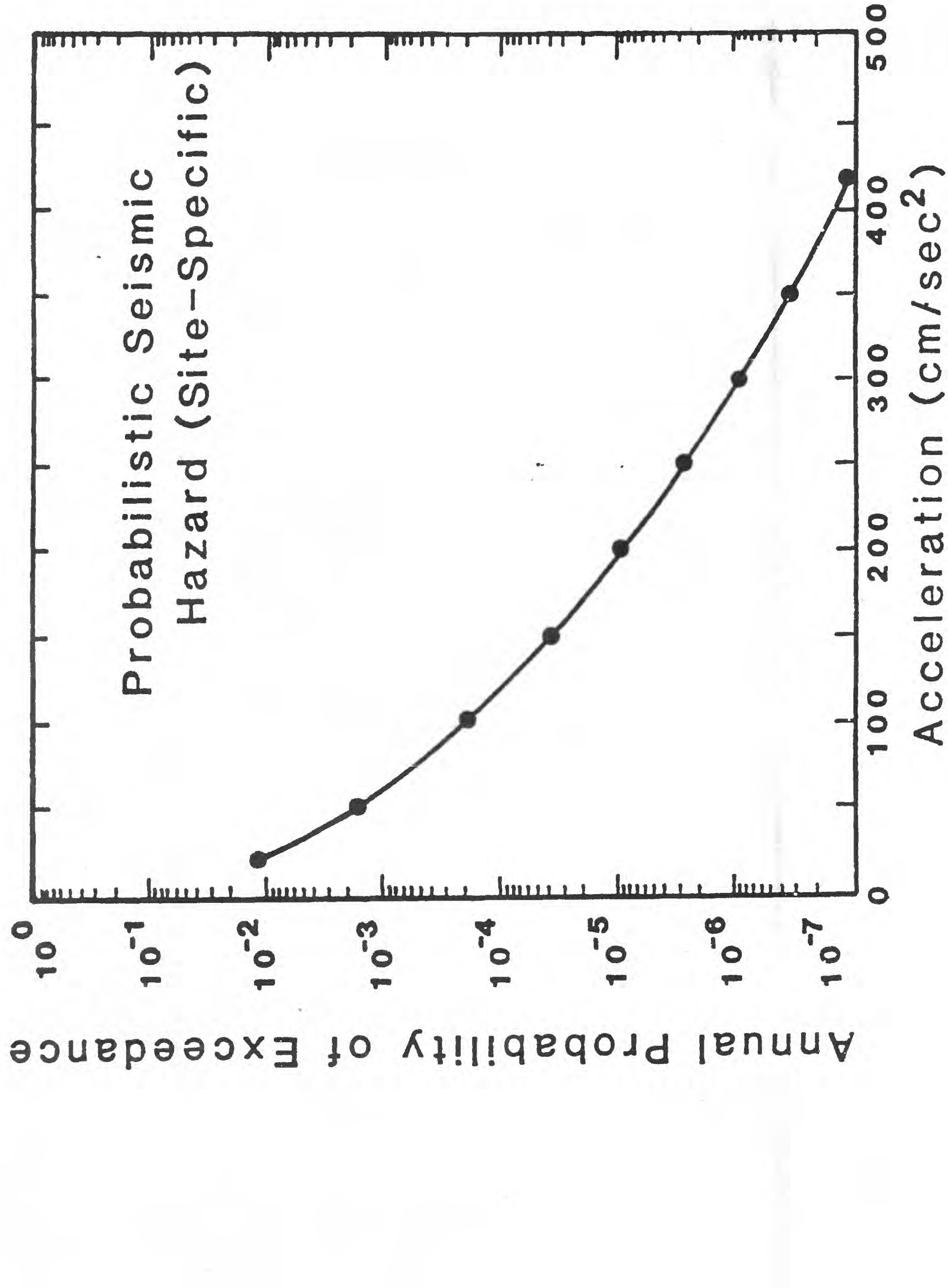

Probabilistic Seismic
Hazard (Site-Specific)
Acceleration (cm/sec^2)
0
100
200
300
400
500
Annual Probability of Exceedance
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}

Figure 1

CENTRAL U.S. CRYSTALLINE BASEMENT CRUSTAL AGE (GENERALIZED)

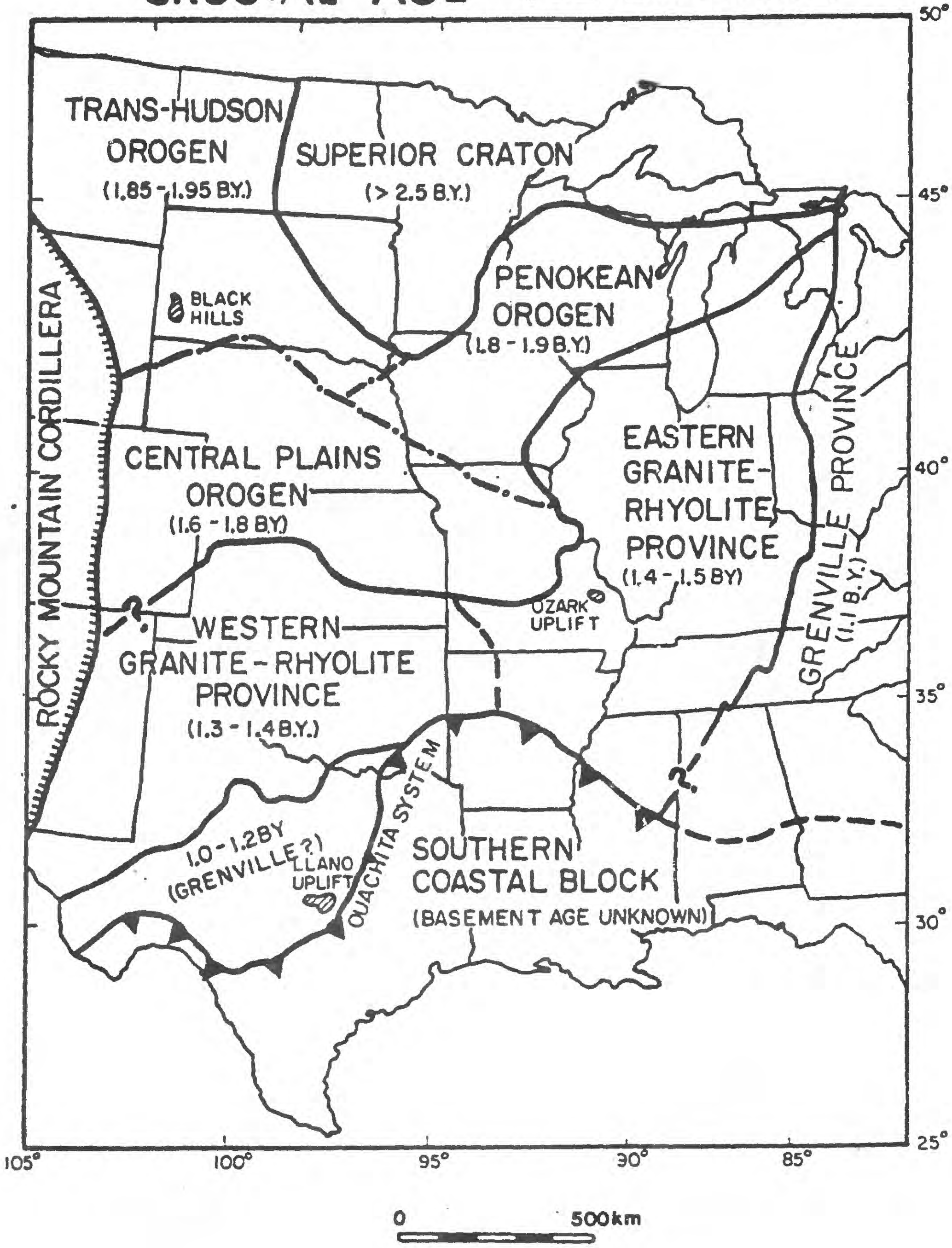


Figure 2

CENTRAL U.S. PRIMARY TECTONIC FEATURES

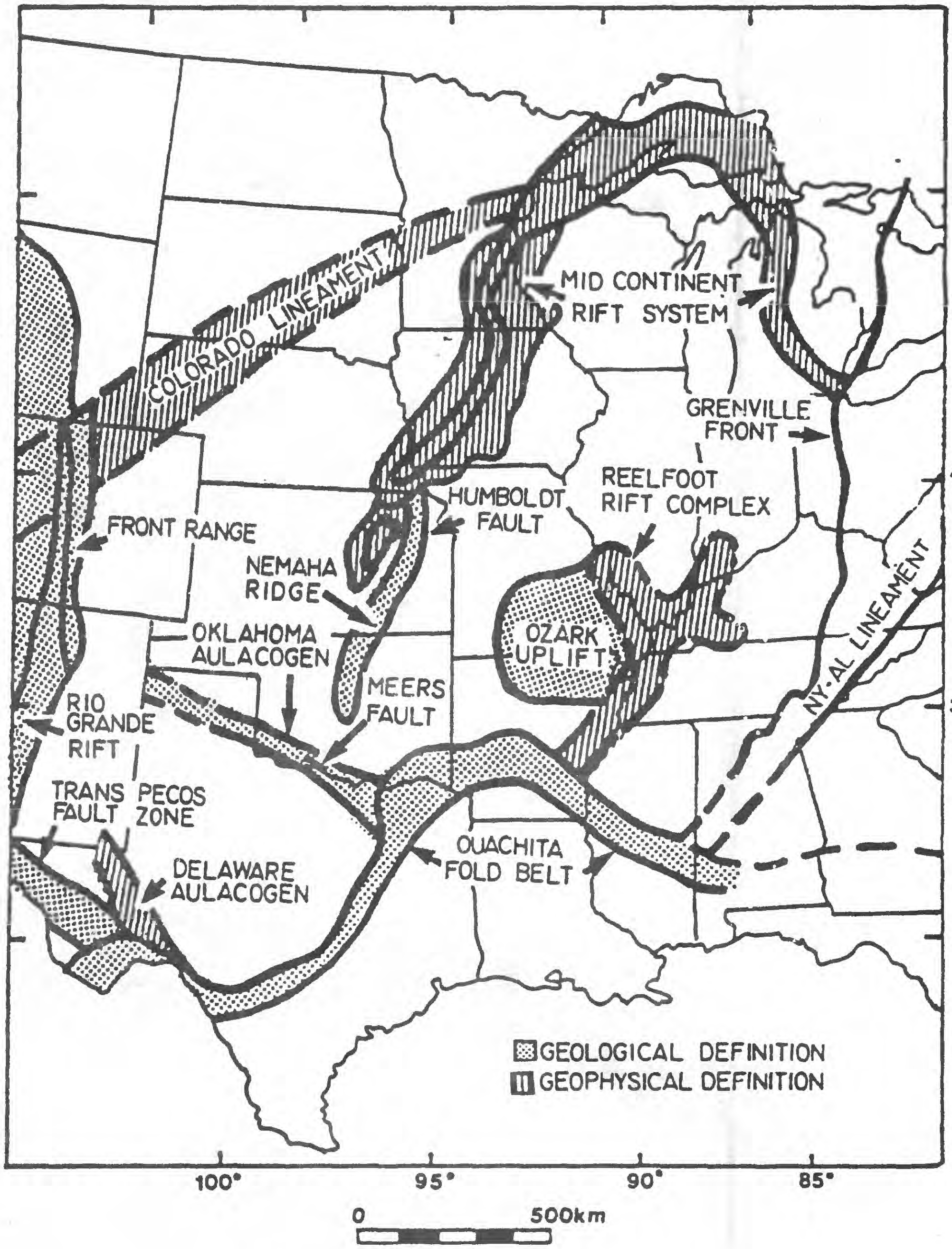


Figure 3

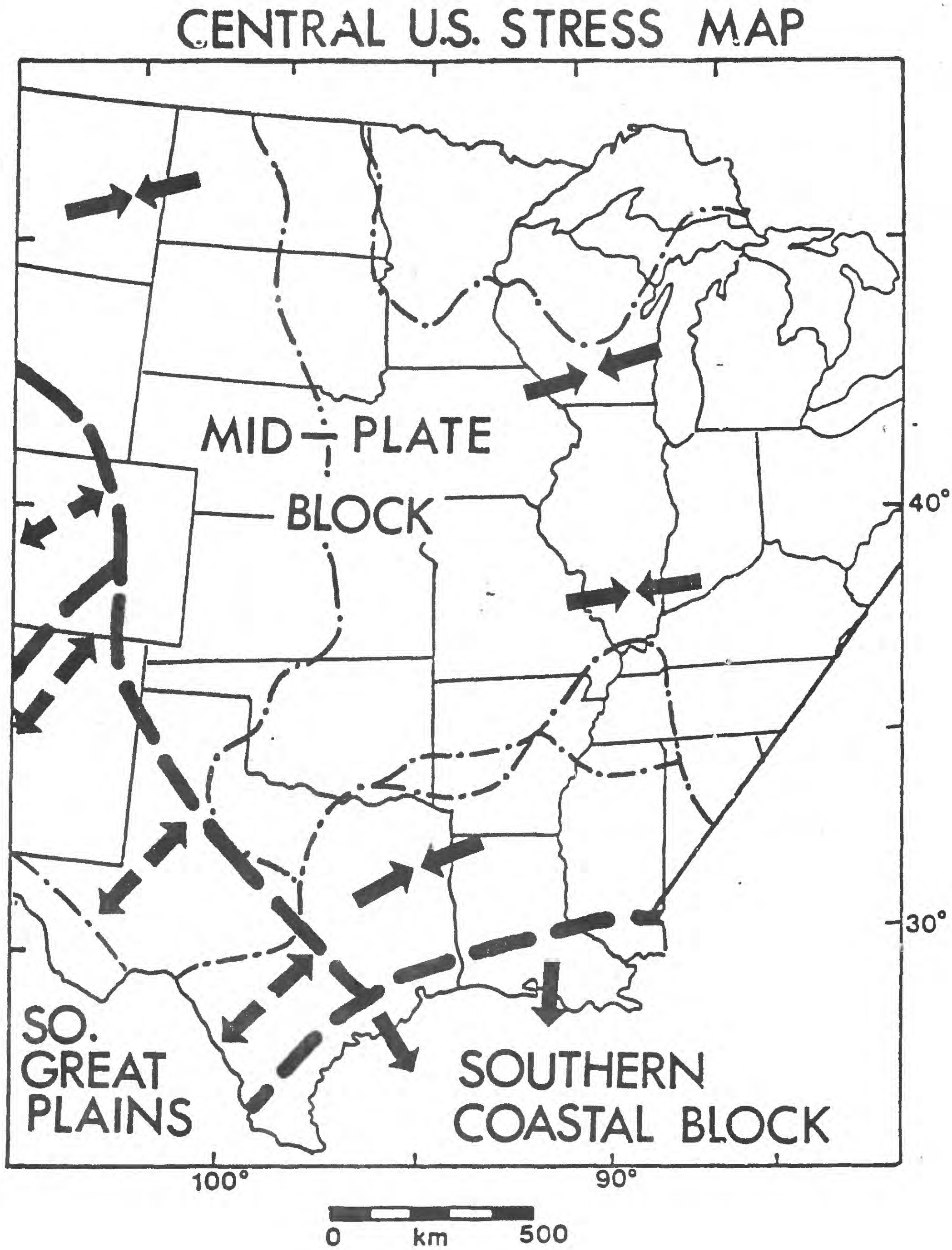

CENTRAL U.S. STRESS MAP
MID-PLATE
BLOCK
40°
30°
SO.
GREAT
PLAINS
SOUTHERN
COASTAL BLOCK
100°
90°
0 km 500

Figure 4

Central United States Seismicity 1627 - 1985
[EPRI, 1986]

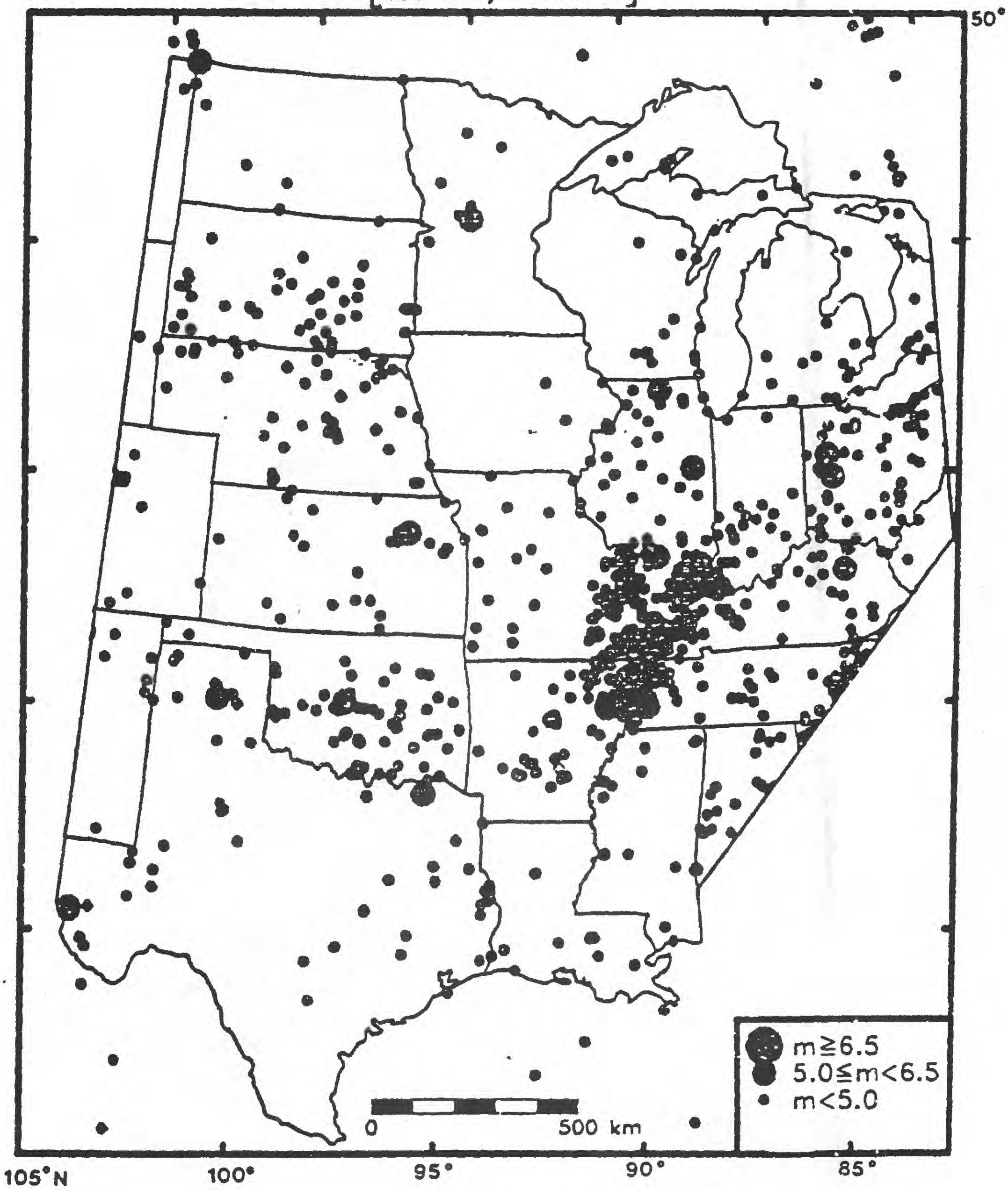


Figure 5

Central United States Seismicity 1811 - 1987
Magnitude ≥ 5.0

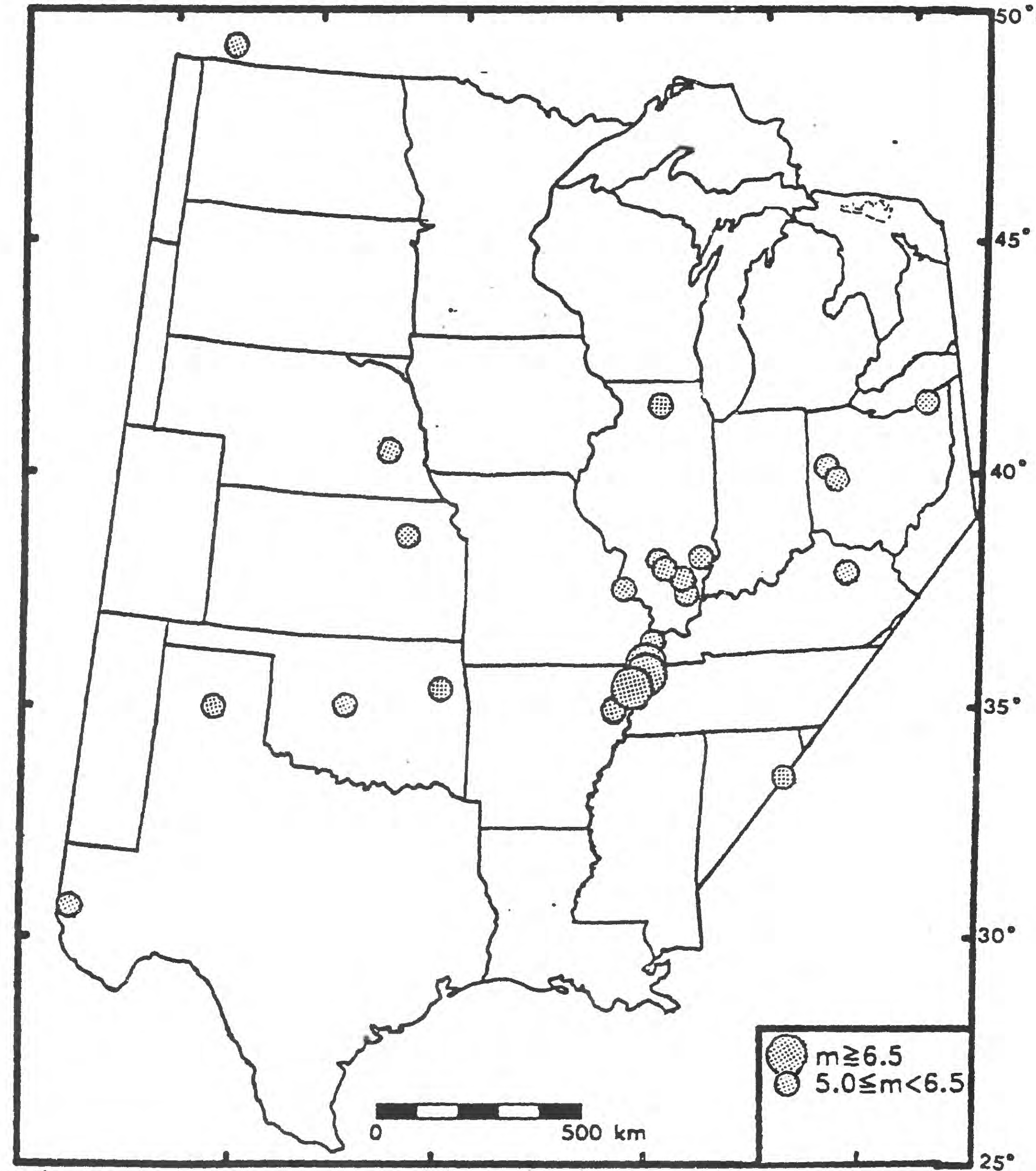
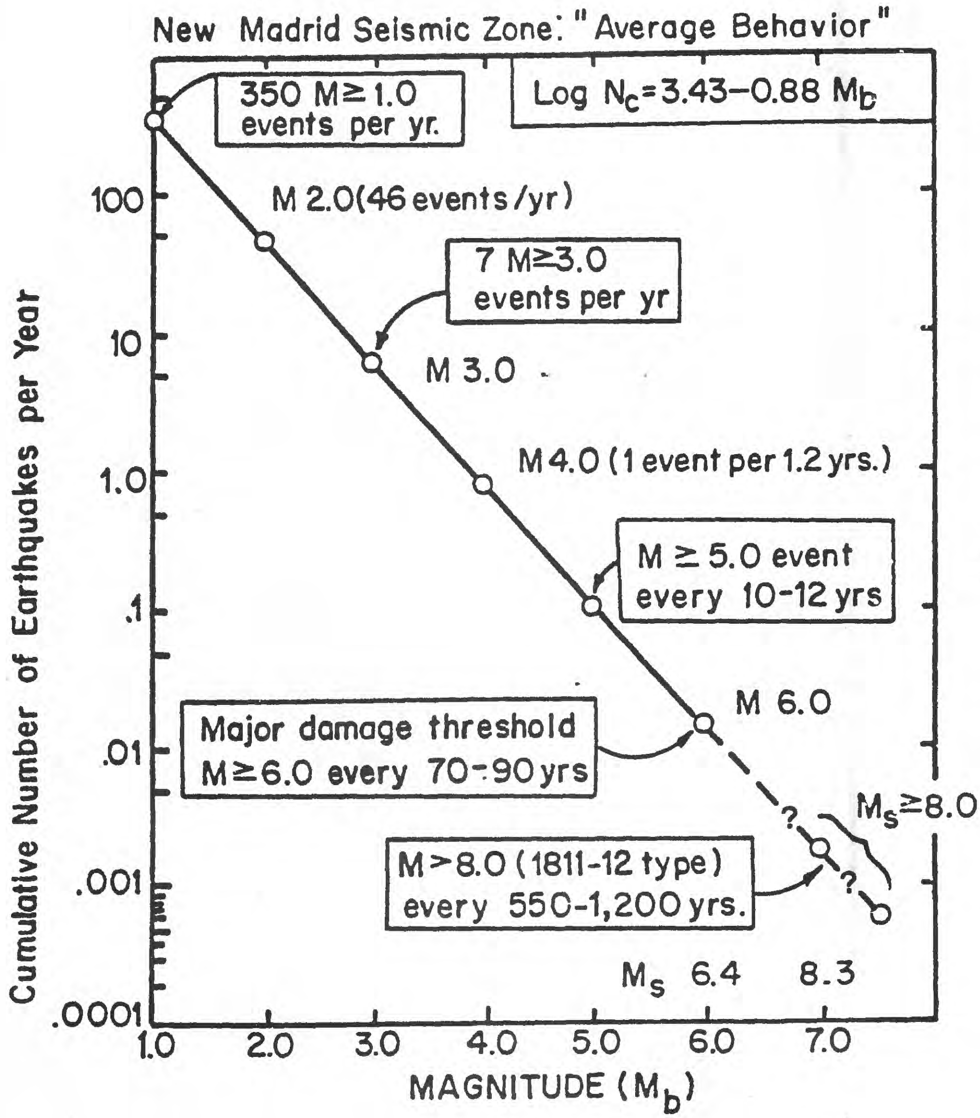


Figure 6



New Madrid Seismic Zone: "Average Behavior"
350 M≥1.0 events per yr.
Log N_c=3.43−0.88 M_b
M 2.0(46 events/yr)
7 M≥3.0 events per yr
M 3.0
M 4.0 (1 event per 1.2 yrs.)
M ≥ 5.0 event every 10-12 yrs
Major damage threshold M≥6.0 every 70-90 yrs
M 6.0
M_s≥8.0
M>8.0 (1811-12 type) every 550-1,200 yrs.
M_s 6.4 8.3
Cumulative Number of Earthquakes per Year
100
10
1.0
.1
.01
.001
.0001
1.0
2.0
3.0
4.0
5.0
6.0
7.0
MAGNITUDE (M_b)

Figure 7

New Madrid Seismic Zone 74 -87

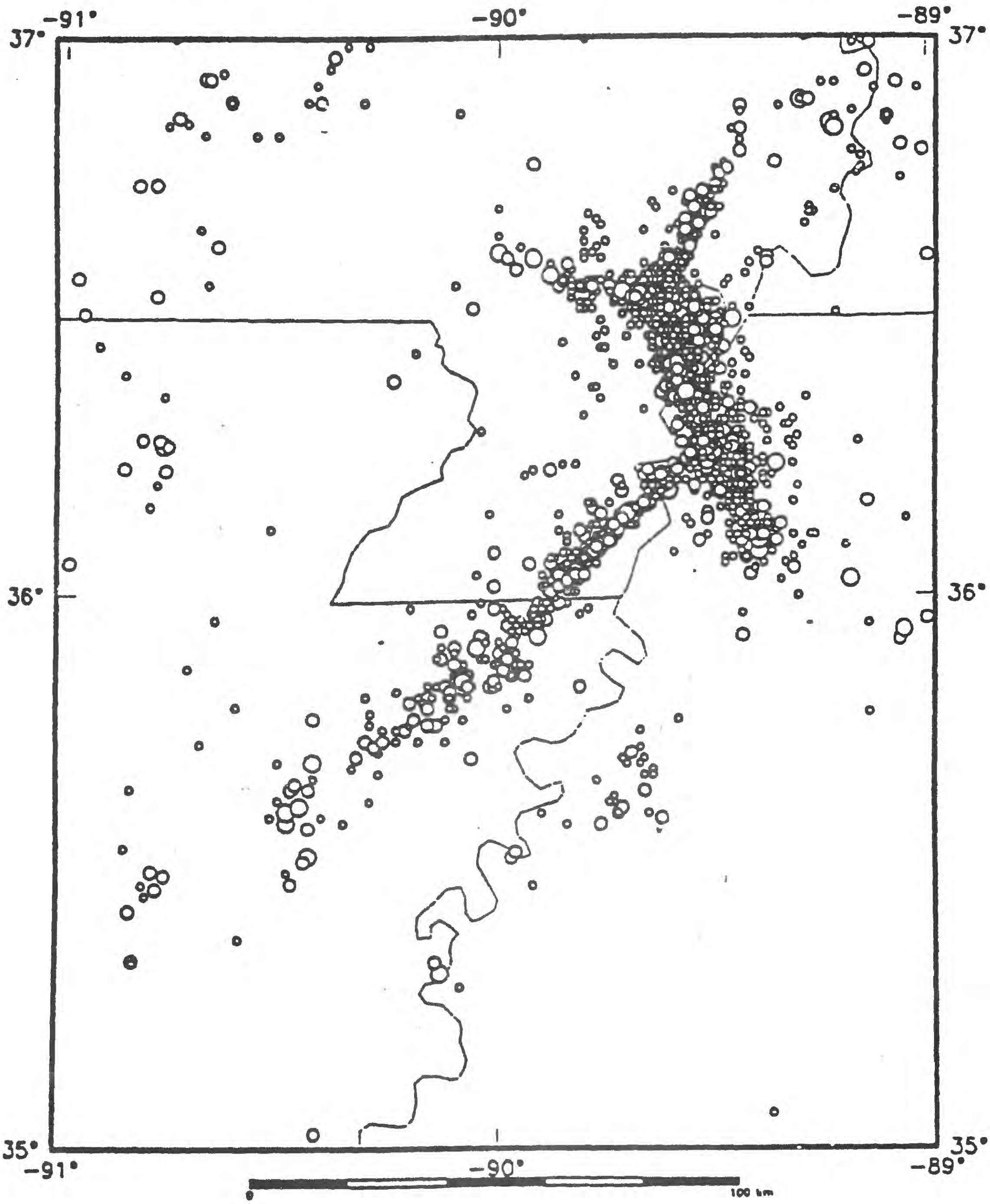


Figure 8

CENTRAL U.S. STUDY AREA

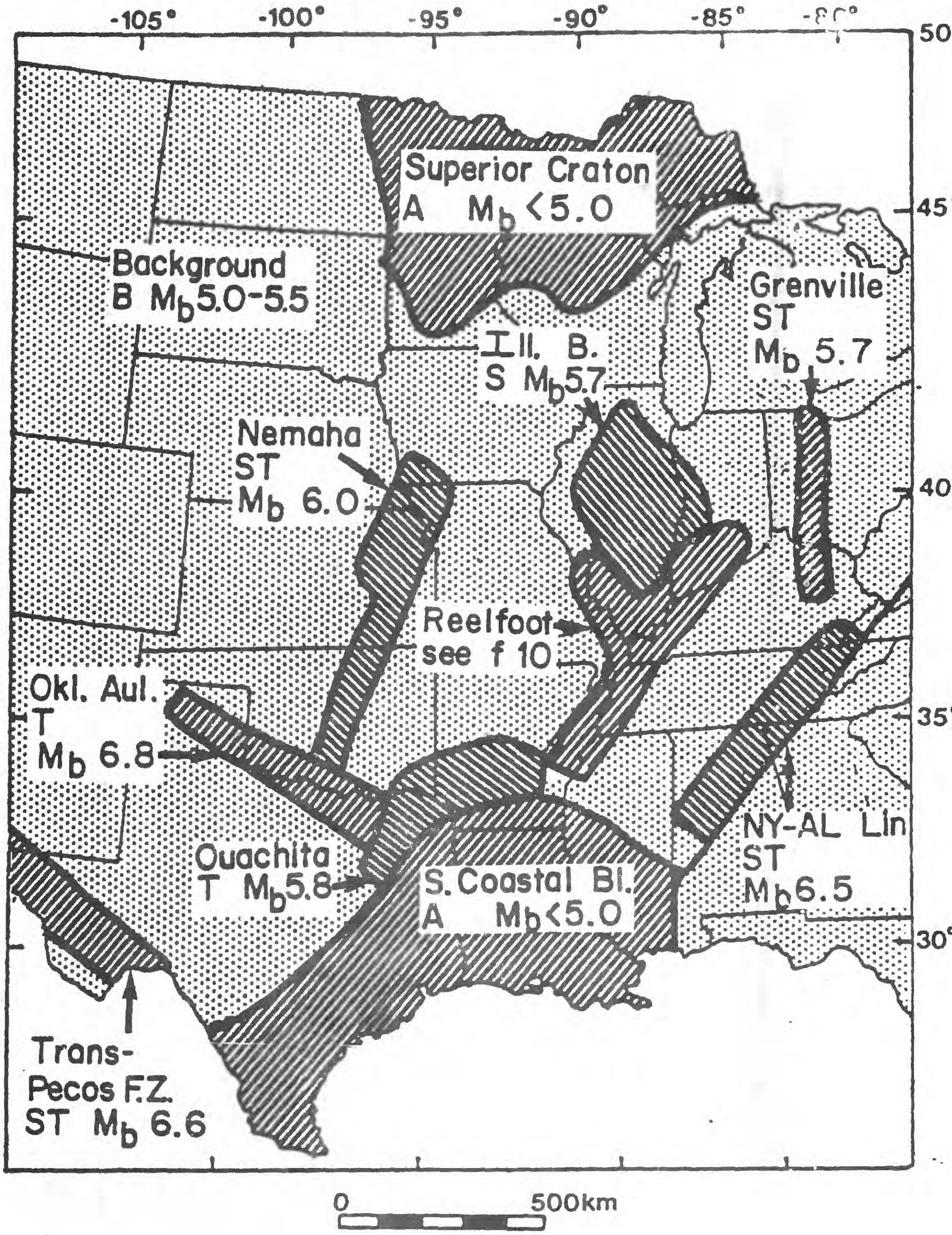


Figure 9

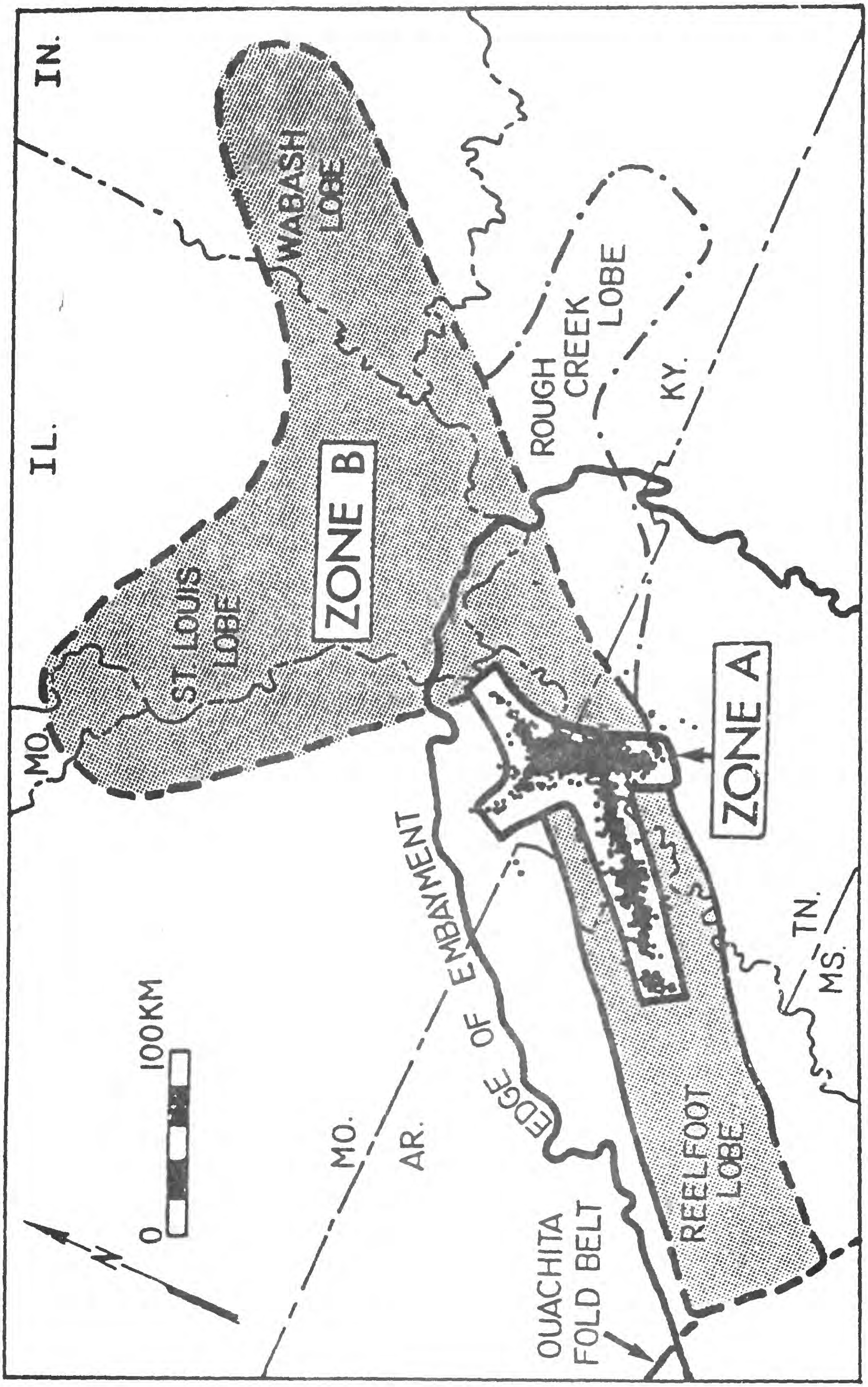

IN.
IL.
MO.
ZONE B
WABASH LOBE
ST LOUIS LOBE
ROUGH CREEK LOBE
KY.
ZONE A
TN.
MS.
MO.
AR.
EDGE OF EMBAYMENT
REELFOOT LOBE
OUACHITA FOLD BELT
0
100KM
N

Figure 10

The Knowledge Base for Assessing Earthquake Hazards and Risk in the Mississippi Valley Region

By

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Abstract

The Mississippi Valley Region has the classic problem of earthquake hazard mitigation. The region has a low probability for the occurrence of damaging earthquakes like those that struck the region in the winter of 1811-1812. However, it has a high probability for experiencing damage, economic loss, deaths and injuries, and loss of function from the physical effects that are expected to be generated when earthquakes like these recur. To prepare for their inevitable recurrence as a function of the seismic cycle of the New Madrid Seismic Zone, assessments are made to define the potential severity and spatial extent of:

- o ground shaking,
- o ground failure (liquefaction and lanslides),
- o surface fault rupture,
- o regional tectonic deformation,
- o seiches,
- o fire,
- o flooding from dam failure, and
- o aftershocks.

These assessments of the physical effects (hazards) are integrated with the inventory of buildings, facilities, and lifeline systems to determine the risk in terms of potential:

- o damage,
- o deaths,
- o injuries,
- o economic losses, and
- o loss of functions.

Public officials, in cooperation with sientists, engineers, architects, urban planners, and emergency managers use hazard and risk assessments to devise, adopt, and implement seismic safety policies in their communities.

INTRODUCTION

An assessment of the earthquake hazards (physical phenomena accompanying an earthquake) and risk (chance of loss from these phenomena) is a complex task requiring multidisciplinary investigations. These investigations are designed to answer the following questions:

- o Where have earthquakes happened in the past?
- o What happened in past earthquakes?
- o What can happen in future earthquakes?
- o How frequently on the average do earthquakes of magnitude 5.5 and greater occur?
- o How severe are the physical effects of earthquakes of magnitude 5.5 and greater expected to be?
- o What kinds of damage will these physical effects cause to the buildings, facilities, and lifeline systems that are at risk?
- o What have communities done to keep these physical effects from causing damage, deaths, injuries, economic loss, and loss of function?
- o What else can be done to mitigate or reduce potential losses in each community?

By analyzing the geologic, geophysical, seismological, and engineering data, realistic assessments can be made of the potential severity and spatial extent of:

- o ground shaking,
- o ground failure (liquefaction and landslides),
- o surface fault rupture,
- o regional tectonic deformation,
- o seiches,
- o fire,
- o flooding from dam failure, and
- o aftershocks.

This information can be integrated with the inventory of buildings, facilities, and lifeline systems to determine the risk.

The Mississippi Valley Region has the classic problem of earthquake hazard mitigation. The problem has two parts:

- o The region has a low probability for the occurrence of damanging earthquakes like those that struck in 1811-1812.

- o The region has a high probability for experiencing damage, economic loss, and loss of life from thephysical phenomena generated by such earthquakes when they recur.

To accomplish an assessment of earthquake hazards and risk in the Mississippi Valley, the following basic data are required:

- o The earthquake history.
- o Isoseismal maps.

- Information on the New Madrid Seismic Zone and other earthquake sources.
- Earthquake recurrence relations.
- Seismic wave attenuation.
- Soil Response.

These basic data will be discussed in the following sections.

EARTHQUAKE HISTORY OF THE MISSISSIPPI VALLEY REGION

The earthquake history of the Mississippi Valley Region is dominated by the series of great (magnitudes of 8 or greater) earthquakes that ruptured the New Madrid Seismic Zone (Figure 1) in the winter of 1811-1812. On December 16, 1811, three earthquakes ruptured the entire southern segment of the New Madrid Seismic Zone, a length of about 90 miles (150 km) which extends from a point in eastern Arkansas 25 miles (40 km) northwest of Memphis to Reelfoot Lake in northwestern Tennessee. These earthquakes had magnitudes (M_s) of 8.6 (2:30 a.m.), 8.0 (8:15 a.m.), and 8.0 (noon). On January 23, 1812, another great earthquake having a magnitude of 8.4 ruptured the central segment of the fault, a length of about 45 miles (75 km). On February 7, 1812, the last and largest earthquake in the series having a magnitude of 8.8 occurred near the town of New Madrid, rupturing the entire 60-mile-long (100 km) northern branch of the fault zone. Between the occurrence of the first earthquake on December 16, 1811, and March 15, 1812, the aftershock sequence included:

- 5 earthquakes of magnitude (M_s) 7.7
- 10 earthquakes of magnitude 6.7
- 35 earthquakes of magnitude 5.9
- 65 earthquakes of mangitude 5.3
- 89 earthquakes of magnitude 4.3

Since 1812, only two earthquakes of magnitude (M_s) greater than 6 have occurred in the Mississippi Valley Region. Both of them occurred in the New Madrid Seismic Zone. They were:

- A magnitude 6.7 earthquake located near Charleston, Missouri. It occurred on October 31, 1895, near the northern end of the New Madrid Fault Zone and caused chimney, wall, and foundation damage in St. Louis.

- A magnitude 6.3 earthquake located in Arkansas. It occurred on January 4, 1843, at the extreme southern end of the fault about 25 miles (40 km) northest of Memphis. It caused structural damage in Memphis, Southwest Tennessee, Northeast Arkansas, and the northwest corner of Mississippi.

In historic times, 17 moderate-magnitude earthquakes (magnitudes of 4.3 to 5.9) have occurred in the Mississippi Valley Region. Only two of these were in the New Madrid Seismic Zone. Two were in the Wabash Valley, and two were in the Illinois Basin of Southern Illinois. The Wabash Valley is suspected by some experts as the potential loation of a future large earthquake because of the deep (20 km) focal depths.

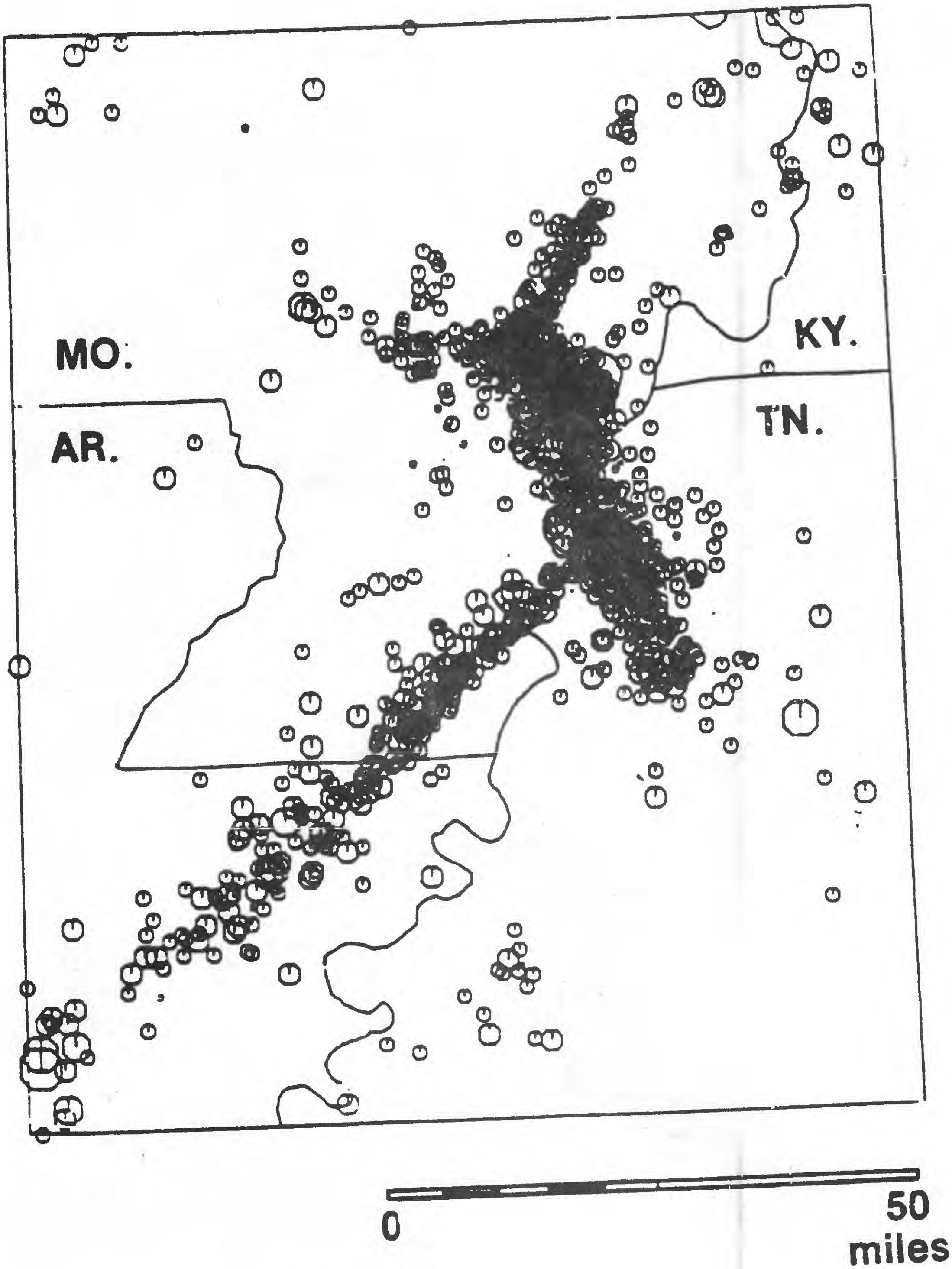

Figure 1: New Madrid Seismic Zone

Isoseismal Maps

In 1973, the late Professor Otto Nuttli of St. Louis University published the results of the reconstruction of the effects of the 1811-1812 earthquakes in terms of Modified Mercalli intensity data (Figure 2). He showed that great earthquakes in the Mississippi Valley can be expected to cause:

- severe structural damage (intensities of IX-XII) over an area of several thousand square miles,
- structural damage (intensities of VIII-IX) over an area of several tens of thousands of square miles, and
- architectural damage and damage to contents (intensities of VI-VII) over an area of several hundred thousand square miles.

The threshold of ground failure occurs at about intensity VI, provided the physical conditions are right.

New Madrid Seismic Zone

The geologic, geophysical, and seismological data show that the New Madrid Seismic Zone is not a fault that breaks the ground surface. Rather, it is a complex zone of buried rifting about 42 miles (70 km) long. It has about 1.2 to 1.8 miles (2 to 3 km) of subsurface structural relief which gravity and magnetic methods have helped to delineate. Numerous microearthquakes located on the seismicity network operated by St. Louis University have helped to outline active segments of the New Madrid Seismic Zone more precisely.

Earthquake Recurrence Relations

The seismicity catalogs have been used to define recurrence relations for the Mississippi Valley Region. The relations are:

- 655 years for earthquake having magnitudes like those of the 1811-1812 New Madrid events.

- 158 years for earthquakes having magnitudes like that of the 1886 Charleston, South Carolina earthquake.

- 38 years for earthquakes having magnitudes like those of the 1843 and 1895 New Madrid events.

- 12 years for earthquakes having magnitudes like that of the 1968 Illinois event.

- 3.5 years for earthquakes having magnitudes like that of the 1980 Kentucky event.

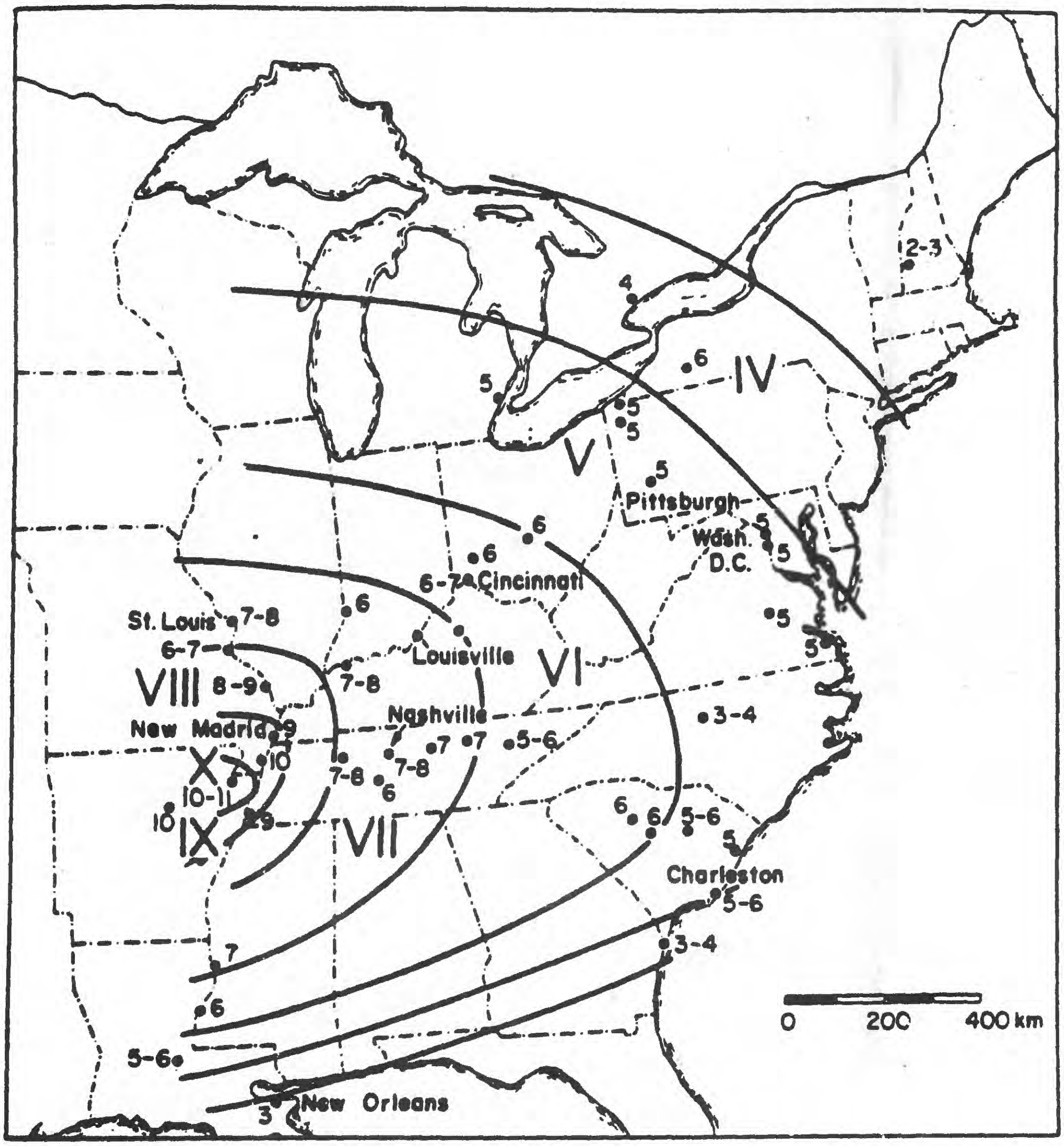

Figure 2: Isoseismal Map 1811-1812 Earthquakes (Nuttli, 1973)

Earthquake Sources (Seismogenic Zones)

Although the New Madrid Seismic Zone is the dominant earthquake source, it is not the only seismogenic zone in the Mississippi Valley Region. Other postulated zones include:

- St. Francois Uplift
- Wabash Valley Fault
- Illinois Basin
- Cincinnati Arch
- Colorado Lineament
- Nemaha Uplift
- Ouachita - Wichita Mountains

These sources are defined on the basis of historical and instrumental seismicity and geologic data.

Seismic Wave Attenuation

The late Professor Otto Nuttli showed that the rate of attenuation of seisic energy in the Mississippi Valley Region is much slower than in the Western United States. This phenomenon creates the possibility for a large area in the Mississippi Valley Region to experience damaging levels of ground shaking. Cities located some distance from the epicentral region of a large- to great-magnitude earthquake could experience damage, especially in cases when the fundamental vibration periods of a building and soil column are closely matched (i.e., a resonant condition).

Soil Response

Soil columns in the Mississippi Valley Region, like many other parts of the world, have physical characteristics that can cause amplification of ground motion in selected period bands. Sites underlain by thin stiff soils can amplify the short-period (high-frequency) components of ground motion; whereas, sites underlain by thick soft sols can amplify the long-period (low-frequency) components of ground motion. Because low-rise buildings are susceptible to short-period ground motion, the damage distribution is controlled to a large extent by the degree to which the response of the building and the soil column are matched. Damage can occur in the upper stores to tall buildings founded on thick soft soils if the building is not designed to accomodate the soil response.

Assessment of the Ground Shaking Hazard

An assessment of the ground shaking hazard must take into account the physical parameters of the:

- earthquake sources,
- propagation paths over which the seismic waves propagate, and
- soil columns underlying the building, facility, or lifeline.

In physical terms, the ground motion generated by the abrupt release of accumulated strain energy in the New Madrid Seismic Zone (or other seismolgenic zones in the Mississippi Valley Region) will consist of:

- P or compressional waves, which are short-period waves that travel through the earth's crust and mantle at about 18,000 miles/hour (8 km/second).
- S or shear waves, which arrive after the P-waves, traveling at about 10,800 miles/hour (4.8 km/second).
- Love waves, which are long-period shear surface waves that arrive after the S-waves, and
- Rayleigh waves, which are long-period surface waves that arrive last at a site.

These four seismic waves comprise the time history of ground motion that depicts how the ground vibrates elastically over time, with the main movement usually being horizontal. The ground motion causes the mass of a building to vibrate, generating inertial forces that are directly related to the building's configuration (i.e., size and shape). The horizontal or lateral forces use up the strength of the building by bending, shearing, or twisting the columns, floors, beams, and walls elastically and inelastically. Eventually, the force of gravity will act to pull down a weakened and distorted building. Probabilistic and deterministic assessments of the ground shaking hazard are typically made. In a probabilistic assessment, the objective is to calculate the probability (e.g., 10 percent) of exceeding a particular level of ground motion (e.g., a level of peak ground acceleration) at a specific site of interest (e.g., a city) during a specific interval of time (e.g., 50 years, the lifetime of an ordinary building). All of the seismogenic sources and travel paths are considered in the analysis. In a deterministic assessment, the objective is to calculate the ground motion for a specific scenario, usually with a specific earthquake source, a given magnitude, and a specific date.

Figure 3 shows some ground shaking hazard curves published by Dr. S.T. Algermissen of the U.S. Geological Survey. These hazard curves were based on a probabilistic assessment and are part of the 1988 edition of the NEHRP Recommended Provisions for Earthquake Resistent Design produced by the Building Seismic Safety Council.

The Ground Failure Hazard in 1811-1812

The 1811-1812 earthquake produced ground failure over a wide area. Sand craters and sandblows, some of which can still be seen, occurred in the Mississippi, Arkansas, Ohio, and St. Francis river flood plains. Liquefaction and landslides occurred over an area of about 6,000 square miles (15,000 square kilometers) in:

- Southeast Missouri,
- western Tennessee, and
- northeastern Arkansas.

Such failures can be expected to occur again.

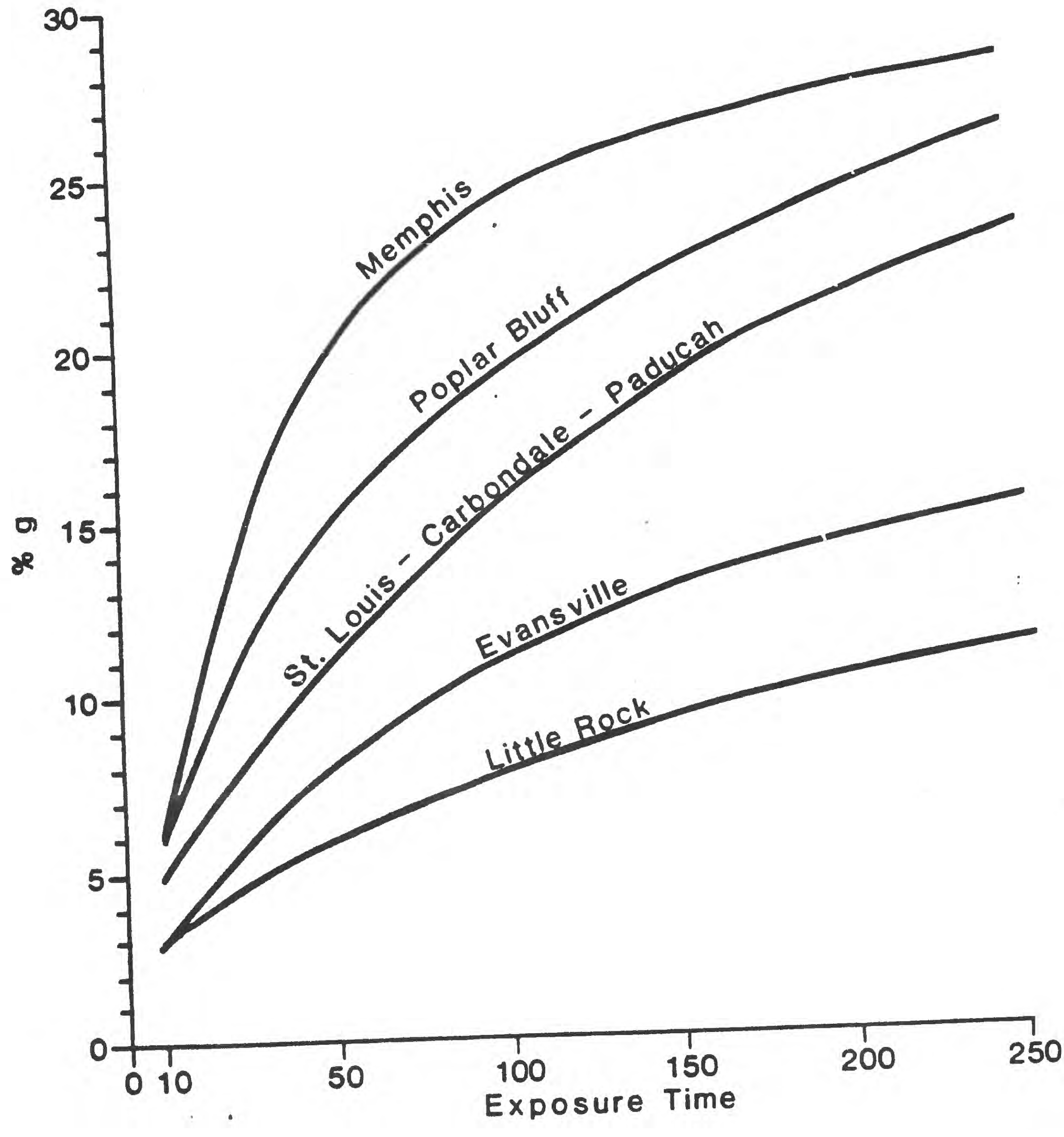

Figure 3: Earthquake Ground Shaking Hazard in Terms of Peak Horizontal Ground Acceleration (Algermissen and others, 1982)

The Surface Fault Ruputure Hazard in 1811-1812

No surface faulting occurred in the 1811-1812 earthquake.

The Regional Tectonic Deformation Hazard in 1811-1812

Vertical uplift and subsidence of 10 to 20 feet occurred in the epicentral region. Also, deep and long rifts formed in the soil. Reelfoot Lake was formed as a consequence of the earthquake.

Assessment of Risk

An assessment of the potential risk (chance of loss) from future earthquakes in the Mississippi Valley Region is a complex task. It requires an integrated evaluation of:

- the earthquake hazards,
- the inventory of structures, facilities, and lifelines exposed to the earthquake hazards, and
- their vulnerability when subjected to the forces and displacements generated by these hazards.

These iterrelations are shown schematically in Figure 4.

A large percentage of the damage and spectacular building collapses in an earthquake are caused by ground shaking, although ground failures also can cause extensive damage. As the ground vibrates, buildings having different frequency-response characteristics begin to vibrate until all are vibrating. Sometimes resonance occurs when the response of the soil column and a building occur at the same period. This physical phenomenon is enhanced when the dominant period of the ground motion occurs at the same period as that of the soil and building response. Such conditions could exist in the Mississippi Valley Region where long-duration surface wave ground motion having dominanat energy in the 1- to 3-second period band propagate great distances because of the low attenuation rates. They are also dispersed in time. These factors increase the likelihood of damage to tall buildings located handreds of miles from the epicenter.

In addition to resonance, adjacent buildings having different heights and different fundamental periods of vibration can vibrate out of phase, pounding one or both of them to pieces. When the elastic strength of the building is exceeded, cracking and various other types of nonlinear behavior occur. These failures can lead to complete collapse of the building.

Some of the buildings, facilities, and lifeline systems are particularly vulnerable to short-period (high-frequency) ground motion; whereas, others are especially vulnerable to long-period (low-frequency) ground motion. Short stifflow-rise buildings and bridges are in the first category; chimenys, water tanks, high-rise buildings, and long-span bridges are in the second category. Buried lifeline systems (e.g., pipelines and tunnels) are more vulnerable to ground failure and fault rupture than to ground motion. Lateral spreads and debris flows can damage highways, railway grades, bridges, docks, ports warehouses, and single family dwellings.

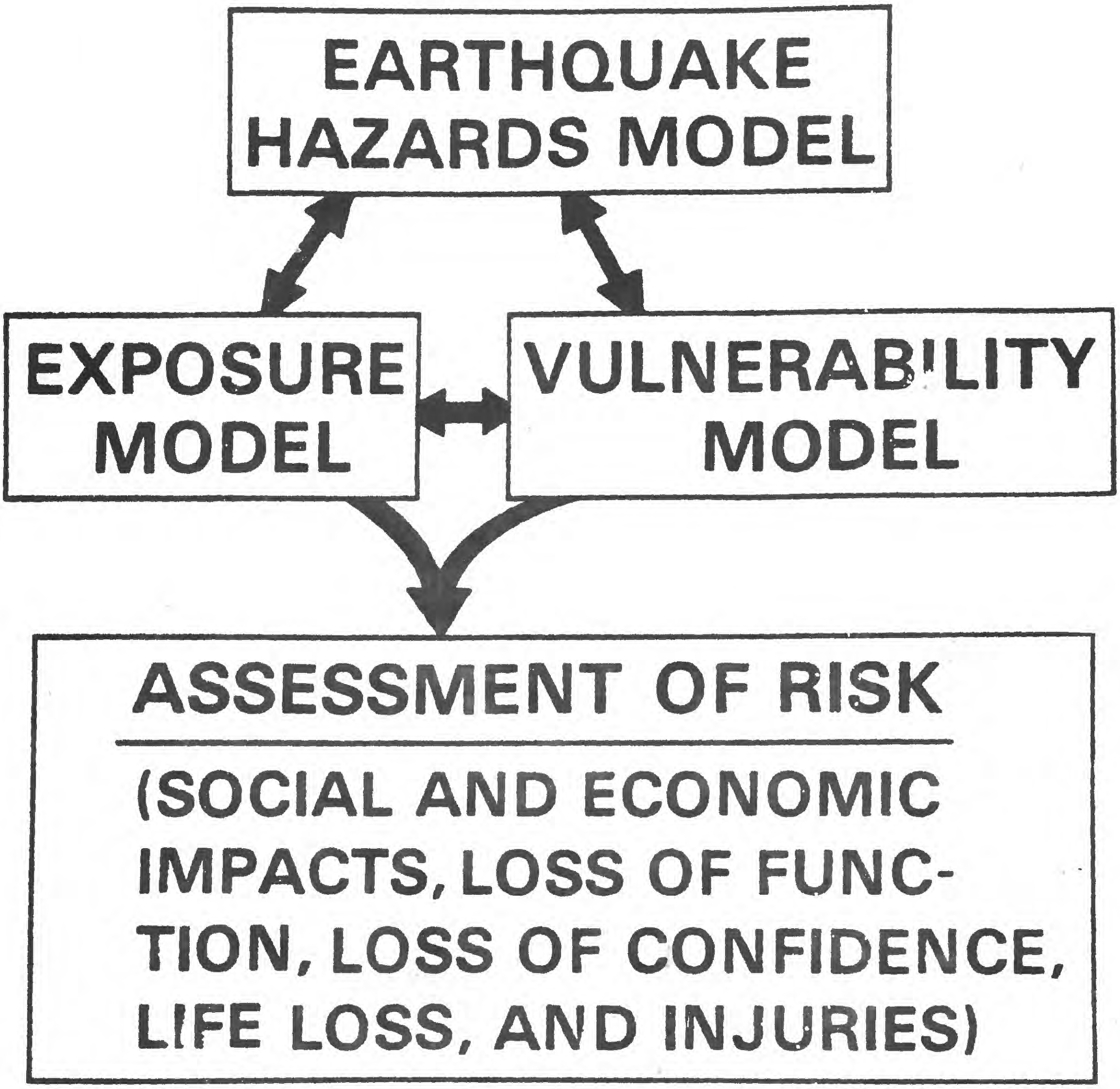

Figure 4: Interrelations of Hazards, Exposure, and Vulnerability.

Background References

Gordon, David W., 1988, Revised Instrumental Hypocenters and Correlation of Earthqauke Locations and Tectonics in the Central United States, U.S. Geological Professional Paper 1364, 69 p.

Algermissen, S.T., 1983, Seismicity of the United States, Earthquake Engineering Research Institute, Monograph, El Cerrito, CA, 148p.

Algermissen, S.T. and others, 1982, Probablistic Estimates of Maximum Acceleration and Velocity in Rock in the Contiguous United States, U.S. Geological Survey Open-File Report 82-1033, 99p.

McKeown, F.A. and Pakiser, L.C. (Editors), 1982, Investigations of the New Madrid, Missouri Earthquake Region: U.S. Geological Survey Professional Paper 1236, 201p.

Nuttli, O.W., 1973, The Mississippi Valley Earthquake of 1811 and 1812, Intensities, Ground Motion, and Amplitudes: Bulletin of the Seismological Society of America, v. 63, pp. 227-248.

TABLE 1: Central Region Seismicity

The seismicity of the central region is dominated by the three great earthquakes that occurred in 1811-12 near New Madrid, Missouri. These earthquakes had magnitudes (M_S) ranging from 8.4 to 8.7 and epicentral intensities ranging from X to XII (Nuttli, 1973). About 15 of the thousands of aftershocks that followed had magnitudes greater than $M_S = 6$. A distribution of earthquakes through 1976 in the central region is given below as well as a listing of the important earthquakes through 1980 (Table 3).

IMPORTANT EARTHQUAKES OF THE CENTRAL REGION THROUGH 1980
[FROM ALGERMISSEN (1983)]

Date	Location	Maximum MMI (I_0)	Magnitude (Approx. M_S)
Dec 16, 1811	New Madrid, Missouri	XI	8.6
Jan 23, 1812	New Madrid, Missouri	X-XI	8.4
Feb 7, 1812	New Madrid, Missouri	XI-XII	8.7
Jun 9, 1838	Southern Illinois	VIII	5.7
Jan 5, 1843	Near Memphis, Tennessee	VIII	6.0
Apr 24, 1867	Near Manhattan, Kansas	VII	5.3
Oct 22, 1882	West Texas	VII-VIII	5.5
Oct 31, 1895	Near Charleston, Missouri	VIII-IX	6.2
Jan 8, 1906	Near Manhattan, Kansas	VII-VIII	5.5
Mar 9, 1937	Near Anna, Ohio	VIII	5.3
Nov 9, 1968	Southern Illinois	VII	5.5
Jul 27, 1980	Near Sharpsburg, Kentucky	VII	5.1

Modified Mercalli Intensity	Number
V	275
VI	114
VII	32
VIII	5
IX	1
X	0
XI	2
XII	1

EARTHQUAKE HAZARD AND RISK EVALUATION IN THE CENTRAL UNITED STATES

S.T. Algermissen
U.S. Geological Survey

INTRODUCTION

The seismicity of the central United States is sufficiently high that qualitative data on damaging earthquakes has been available in some areas for more than 150 years. In addition to the great earthquakes of 1811-12 in southeast Missouri, damaging earthquakes occurred in southern Illinois in 1838, near Memphis, Tennessee, in 1843, near Manhattan, Kansas, in 1867 (and again in 1906), and near Charleston, Missouri, in 1895. Other significant shocks occurred near Anna, Ohio, in 1937 and for several years thereafter. For the area shown in figure 1 (Algermissen, 1983), there has been, on the average, nearly one earthquake per year that has caused at least minor damage (Modified Mercalli VI) since 1811.

The intent in this paper is to provide an overview of the historical seismicity and seismotectonics of the central United States, to discuss the history of seismic zoning efforts in this region, and to provide an introduction to the problem of earthquake economic loss (risk) and the importance of earthquake risk studies in the central United States.

SEISMICITY AND SEISMOTECTONICS

Most of the data for earthquakes in the central United States prior to about 1960 is based on the examination of written reports of shaking (intensity data). The magnitude threshold for much of the mid-west in 1965 was about $m_b = 4.2$, except for a limited areas in Missouri and Illinois where St. Louis University established a local seismograph network in the 1930's. A number of new regional seismograph networks were established in the 1970's in the central United States. The installation of a modern seismograph network in 1974 by St. Louis University in cooperation with the U.S. Geological Survey has greatly improved our understanding of the spatial distribution of seismicity in the most important earthquake zone in the region, the so-called New Madrid Seismic Zone in southeast Missouri. The seismicity of the central Mississippi Valley is shown in some detail in figure 2 (Stauder, 1982). The increased resolution of the New Madrid Seismic Zone provided by the local network established in 1974 and augmented several times since then is shown in figure 3 (Herrmann, 1984).

The seismicity of the central region is dominated by the large earthquakes that have occurred in the Mississippi River Valley in much the same way that the seismicity of the southeastern United States is dominated by the Charleston earthquake of 1886. Exclusive of Alaska, the earthquakes that occurred in the Mississippi Valley in 1811 and 1812 rank as the largest known shocks in North America since European settlement. The 1811-12 earthquake sequence has been extensively investigated by Nuttli (1973, 1981), and the following discussion is taken principally from his comprehensive studies.

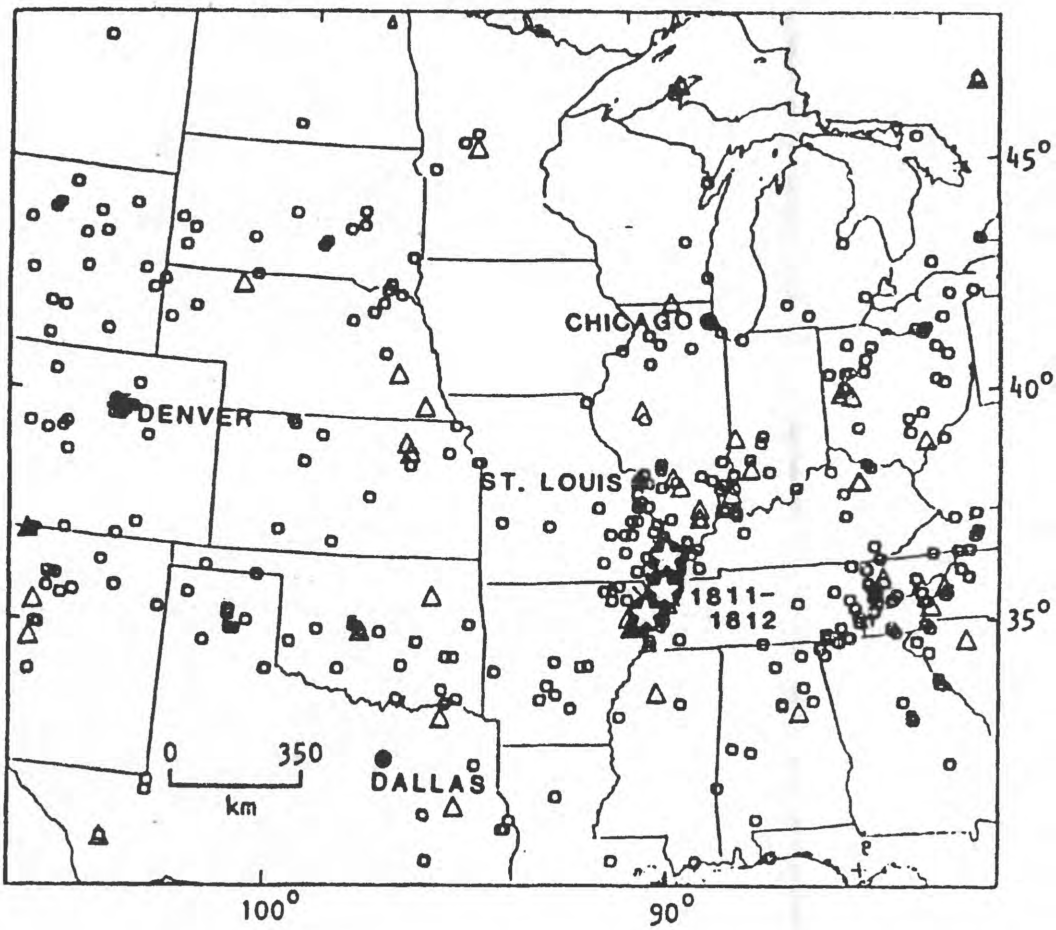

Figure 1. -Seismicity of the Central region, 1811-1976 (Algermissen, 1983). The stars represent earthquakes with maximum MM intensities of IX or greater; triangles represent earthquakes with maximum intensities of VII-VIII; squares represent earthquakes with maximum intensities of V-VI.

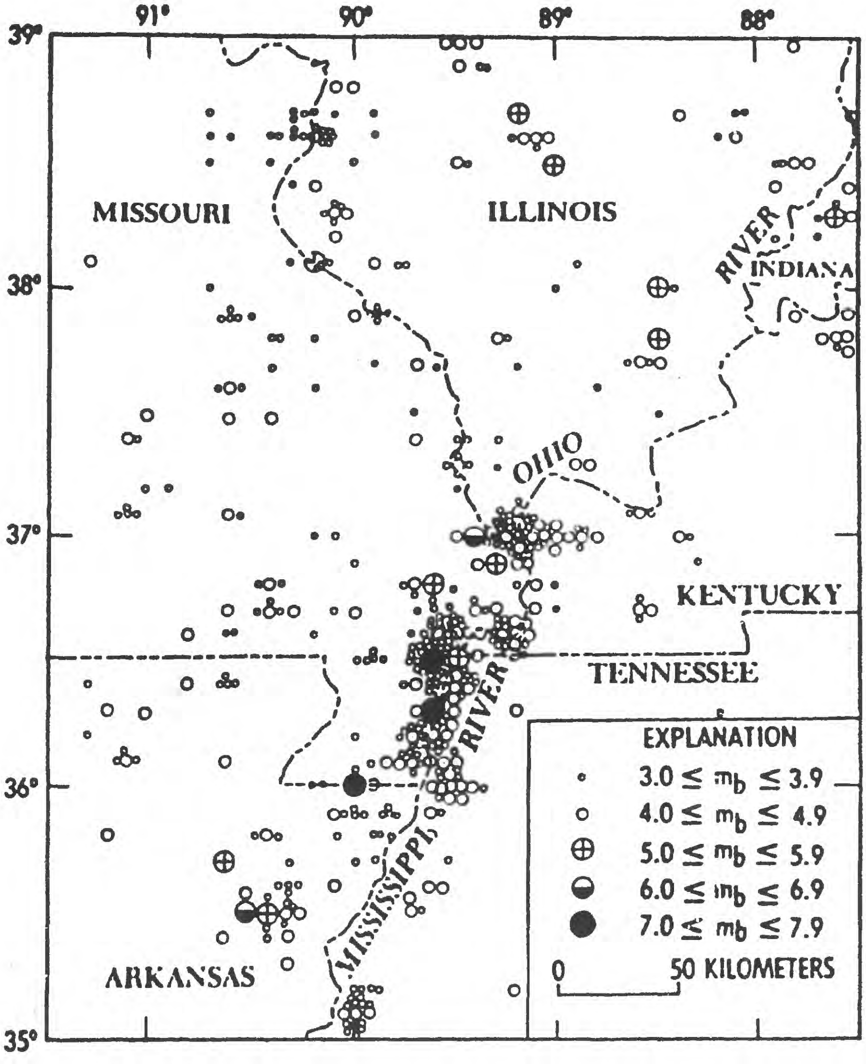

Figure 2. Epicenters of 488 earthquakes of magnitude m_b = 3 and greater occurring in the central Mississippi valley from 1811 to mid-1974 (Stauder, 1982).

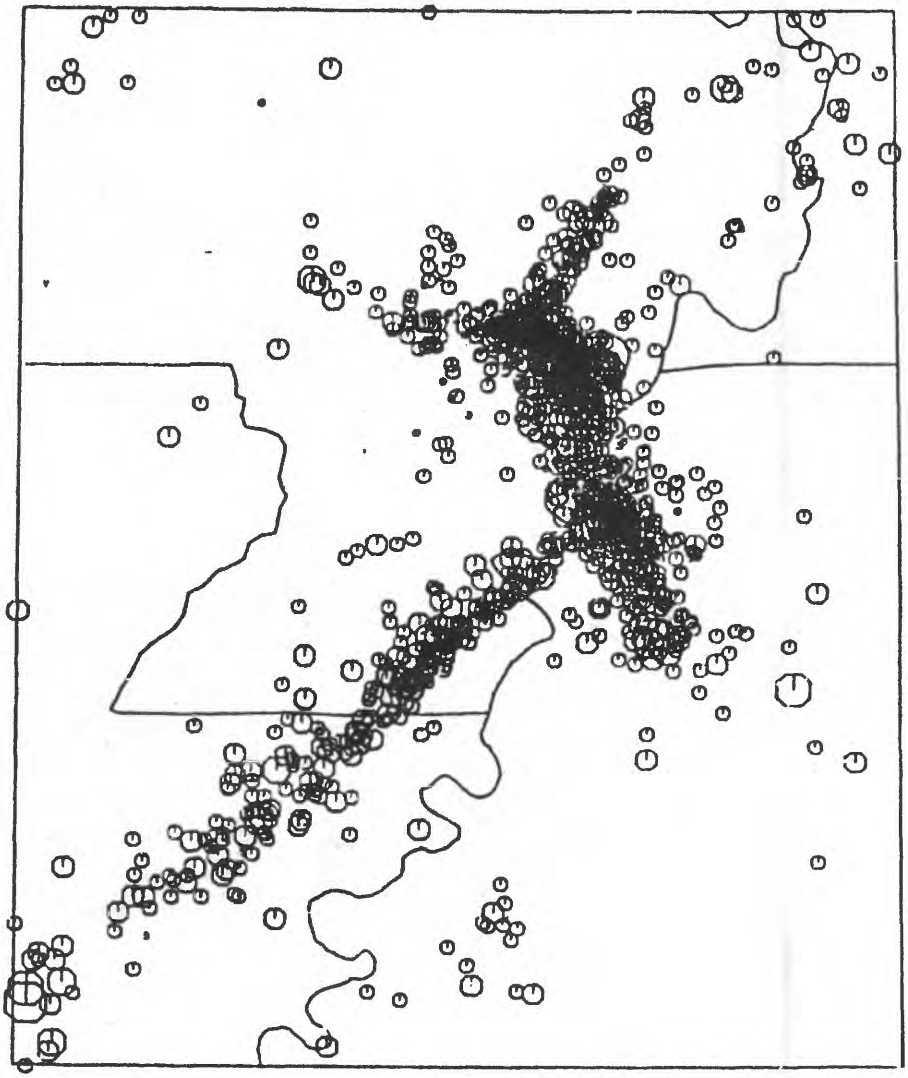

Figure 3. Location of earthquakes detected and located using the dense regional network for the reporting period 1976 - 1982 in the immediate vicinity of New Madrid, Missouri (Herrmann, 1984).

The earthquake sequence began with two major shocks separated by about six hours on December 16, 1811, and was followed by numerous aftershocks (table 1). An isoseismal map prepared by Nuttli (1981) is shown in figure 4. Soil liquefaction, as well as regional subsidence and uplift, was widespread. Local landsliding was common, especially along the rivers. A number of islands in the Mississippi River disappeared. The other two principal shocks of the series occurred on January 23 and February 7, 1812.

Masonry and stone structures were damaged to distances of 250 km. Chimneys were destroyed in Louisville, Kentucky, about 400 km from the earthquakes. Lesser chimney damage was found at distances of over 600 km. The earthquakes were felt south to the Gulf Coast, southeast to the Atlantic and northeast to Quebec. No reports of the earthquakes were available to the west, and this is reflected in figure 4. The third and probably largest shock of the series occurred on February 7, 1912, and was located about 10 to 20 km west of the town of New Madrid. The January 23 event is believed to have occurred roughly equidistant between the December 16 shocks and the February 7 shock, but its epicenter is largely speculative (see figure 2).

The December 16, 1811, earthquake had (with the possible exception of the shock on February 7, 1812) the largest potential damage area and felt area known in the earthquake history of the United States. The area of potential damage (taken as the area shaken at an intensity level of VII or greater) has been estimated as 600,000 km^2 (Nuttli, 1973). For comparison, a reasonable extrapolation of the intensity VII and greater area of the 1964 Alaska earthquake yields an area of about 210,000-250,000 km^2. The 1906 San Francisco earthquake had an area with intensity greater than or equal to VII of about 30,000 km^2.

In contrast to the usual occurrence of a single principal shock followed by a series of aftershocks, the 1811-12 earthquake series had four large shocks, each of which was followed by aftershocks, many of them very large. There were more than 1600 aftershocks large enough to be felt in the first three months following the December 16, 1811, event. About as many earthquakes occurred in the Mississippi Valley area in these three months as occurred in southern California in the 40-year period from 1983 through 1972; aftershocks continued until at least 1817. The locations of these aftershocks are not known, but it is possible that they occurred over a considerably larger area than did the three main shocks.

Fuller (1912) has described the widespread uplift and subsidence in the New Madrid area, although the association of some of the features described by Fuller with the 1811-12 series has been questioned. No surface faults clearly associated with the earthquake have been identified. This suggests that at least the large earthquakes are not extremely shallow (<15 km) and probably occurred at depths of 15-30 km. Depths greater than about 30 km for large shocks would not seem likely, based on the observation that the larger earthquakes known to have occurred in the Midwest (in 1811-12) had long aftershock sequences, a characteristic of large shallow earthquakes. Further evidence that these were shallow earthquakes is that many of the small earthquakes of recent years have been well located and are known to be quite shallow.

Table 1. Principal Shocks and Aftershocks of the Mississippi Valley 1811-1812 Earthquake Series

Principal Shocks		Magnitudes m_{bLg}	M_s	Maximum MMI
[1]Dec. 16, 1811	2:15 a.m.	7.2	8.6	XI
[2]Dec. 16, 1811	8:15 a.m.	7.0	8.2	XI
[1]Jan. 23, 1812	9:00 a.m.	7.1	8.4	X-XI
[1]Feb. 7, 1812	3:45 p.m.	7.4	8.7	XI-XII

Aftershocks -- [2]Six earthquakes $6.2 \leq m_{bLg} \leq 7.0$

-- [2]197 earthquakes $5.2 \leq m_{bLg} \leq 6.2$

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[1]Nuttli, Otto, 1981

[2]Street, R., and Nuttli, Otto, 1984

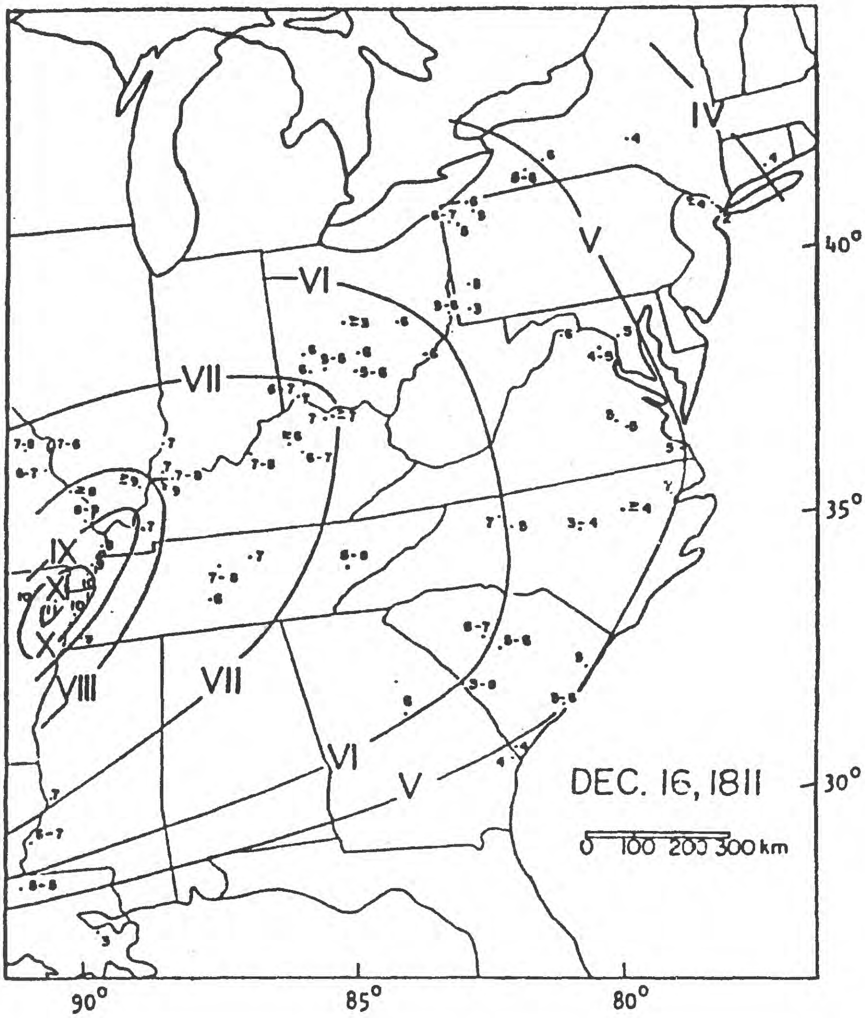

Figure 4. Isoseismal map of the December 16, 1811, earthquake (Nuttli, 1981). The arabic numbers give the Modified Mercalli intensities at each data point.

Important earthquakes in the central region exclusive of the 1811-12 series have been listed by Algermissen (1983). A listing of the damaging earthquakes in the central Mississippi Valley may be found in Nuttli (1982). The completeness of the historical record of seismicity for the central region is related to the westward settlement of the area. The seismicity is reasonably well known for nearly 200 years in the eastern portion and for only about 100 years in the area west of Missouri, west of about 95°W longitude. It is believed that earthquakes in the region with epicentral Modified Mercalli intensities of VI or greater have been completely reported after settlement of these areas (Nuttli, 1979). The instrumental network of seismograph stations over much of the central region still remains inadequate to provide significant seismotectonic data, to outline active faults, and to improve the evaluation of the seismic hazard.

In the New Madrid Seismic Zone, the pattern of contemporary seismicity emerges clearly in figure 3 even though only six years of data from the microearthquake network are shown. Figure 2 also shows the approximate epicenters of the three main shocks of the 1811-12 series and two other important earthquakes that occurred in the zone, one in 1843 (I_o = VIII) and the other in 1895 (I_o = IX). It is interesting to note in figure 2 that the epicenters of the 1843 and the 1895 earthquakes are located, respectively, near the south and north ends of the principal microearthquake activity. Figure 5 shows the relationship of the microearthquake data to regional geological features and illustrates many of the results of research efforts in the past ten years in the Mississippi River Valley. The microearthquakes define line segments: (1) from Marked Tree, Arkansas to Ridgely, Tennessee, striking northeast; (2) from south of Ridgely to about 20 km west of New Madrid, Missouri, striking slightly west of north; and (3) from the vicinity of New Madrid to Charleston, Missouri, striking northeast (Hamilton, 1981).

The principal seismicity occurs in the northern Mississippi embayment, a south plunging wedge of Cenozoic sedimentary rocks. Specifically, the New Madrid seismic zone is located in a southwest-northeast striking graben or downthrown block about 70 km wide and at least 200 km long. This graben is believed to have formed in the later Precabrian era during a period of continental rifting (Hildenbrand and others, 1983; Sawkins, 1976; and Ervin and others, 1975). The rift structure was defined principally on the basis of the interpretation of magnetic data (Hildenbrand and others, 1977; 1983). Magnetic data have also identified several plutons (intrusions of igneous rock into the basement) that seem to bound the rift, particularly on the north, west and east sides. Seismic reflection data indicate repeated faulting along preexisting zones of weakness in the rift (Zoback and others, 1980). Very old Continental rifts appear to be important in concentrating seismicity not only in the New Madrid area but elsewhere in the central and eastern United States, because they are weak zones in the crust that may be reactivated repeatedly if they are properly oriented in the present stress field. For a more complete discussion, see Hamilton (1980, 1981) and Zoback and Zoback (1980).

An unanswered question is whether the rift structure identified in the Mississippi Valley is unique in the central United States or whether other similar structures may exist. Damaging earthquakes have also occurred sporadically in the central United States in the Wabash Valley area northeast of the New Madrid zone, along the Ouachita-Wichita mountains in Oklahoma, in

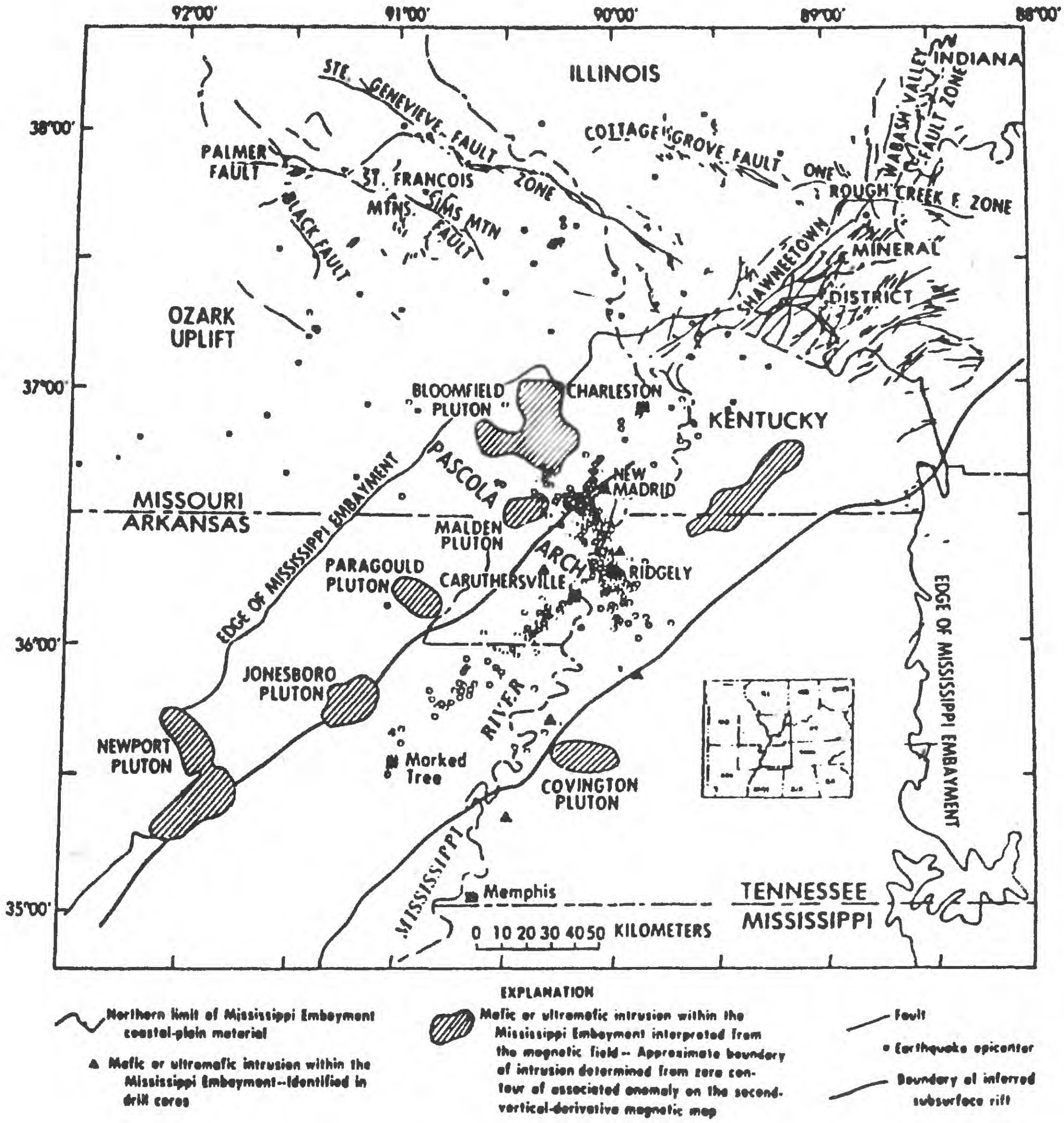

Figure 5. Relationship of earthquake epicenters, plutons, rift boundaries, faults, and major geologic features in the northern Mississippi embayment region. Epicenters, open circles (Stauder and others, 1979: plutons, lined pattern; rift boundaries, heavy solid lines (Hildenbrand and others, 1983 volume); and faults, fine solid lines (Heyl and McKeown, 1978).

northeast Kansas and southern Nebraska, in northern Illinois, in a relatively small area in western Ohio near Anna, and in northern Kentucky. Conclusive correlations between the occurrence of earthquakes in these areas and geologic structures have not been demonstrated, although a number of seismotectonic relationships have been postulated. In contrast to figure 1, which shows that earthquakes with epicentral intensities of V and VI are quite widely distributed throughout the central United States, earthquakes with maximum MM intensities of VII or greater are relatively uncommon in the central United States outside of the Mississippi Valley.

THE DEVELOPMENT OF SEISMIC ZONING IN THE UNITED STATES

An historical approach will be used to review the development of concepts of seismic zoning in the central United States in the context of the development of national ground motion and zoning maps. In this way the seismic hazard in the central United States can be viewed from a national perspective. In 1948, a "Seismic Probability Map" was developed by F.P. Ulrich of the U.S. Coast and Geodetic Survey (Roberts and Ulrich, 1951). This map divided the contiguous United States into four zones numbered 0, 1, 2, 3, where Zone 3 was considered to have the greatest potential for earthquake damage (fig. 6). The map was adopted in 1949 by the International Conference of Building Officials (ICBO) for inclusion in the Uniform Building Code, and became one of the first national zoning maps used for building code purposes in the United States. The numbered zones were used in the code in the development of the lateral force provisions considered appropriate for various parts of the country. Despite the fact that Ulrich developed his map with the aid of some of the leading seismologists in the country, the exact basis for the zones on the map was never made entirely clear by Ulrich in published papers. Figure 6 also displays epicenters of the larger earthquakes that occurred through 1946. The zones were apparently drawn on the basis of the maximum magnitude earthquake that had occurred in each zone and are more or less geometrical in outlines and clearly do not represent differences in ground motion. Thus, at some places on the map zone 3 adjoins zone 1, as, for example, in the Mississippi Valley. Within a few years, the map was withdrawn by the U.S. Coast and Geodetic Survey as misleading and subject to misinterpretation. No map was offered as a replacement.

An important seismic regionalization map was published by Richter in 1958 (Richter, 1959, fig. 7). This map contained several significant advances. It depicted the estimated maximum ground motion rather than the distribution of earthquake epicenters, and it introduced the notion of earthquake recurrence in a qualitative way.

The 1970 edition of the Uniform Building Code (UBC) used a map developed by Algermissen (fig. 8) which has the same numbering scheme (0 through 3) as the Ulrich map. This map is based largely on the maximum Modified Mercalli intensity observed historically in each zone, but the spatial distribution of the intensities has been generalized to take into account some regional geological structures. The paper accompanying the zoning map also contained a maximum Modified Mercalli map, a strain energy release map, and earthquake recurrence curves for various regions of the country. The zoning map was adopted by the UBC in 1970, but the Code did not make use of the frequency of earthquake occurrence information that accompanied the map. In the 1976

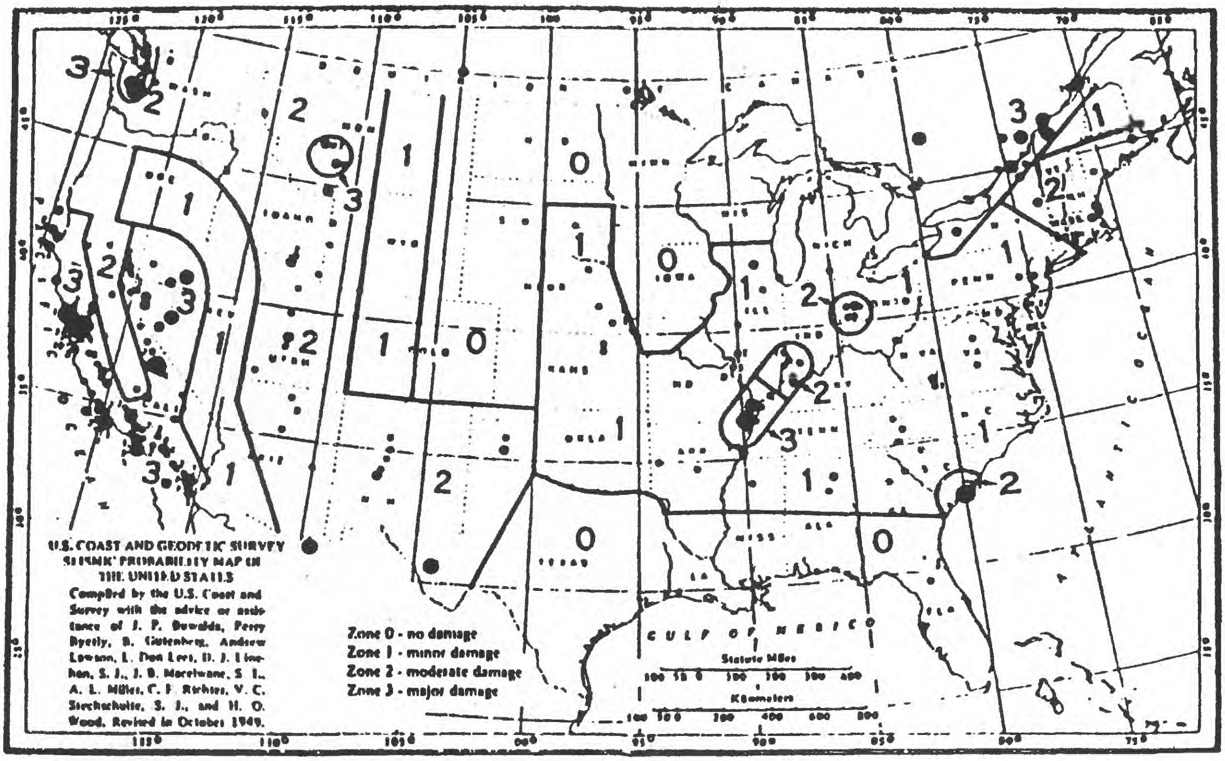

Figure 6. Seismic probability map of the United States developed by Ulrich (1951).

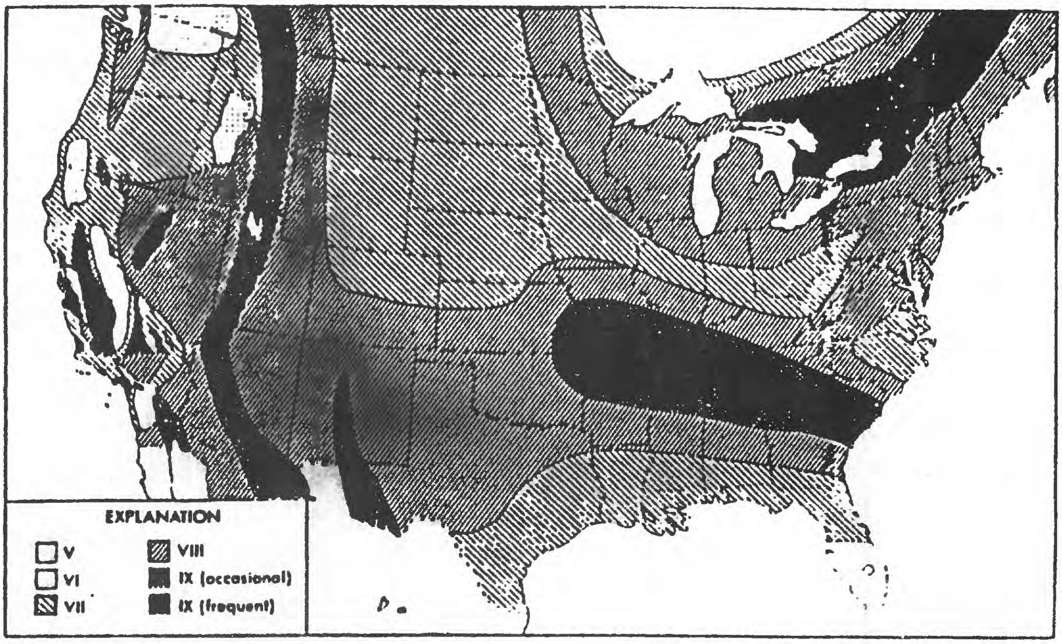

Figure 7. Seismic regionalization map of the conterminous United States published by Richter (1959).

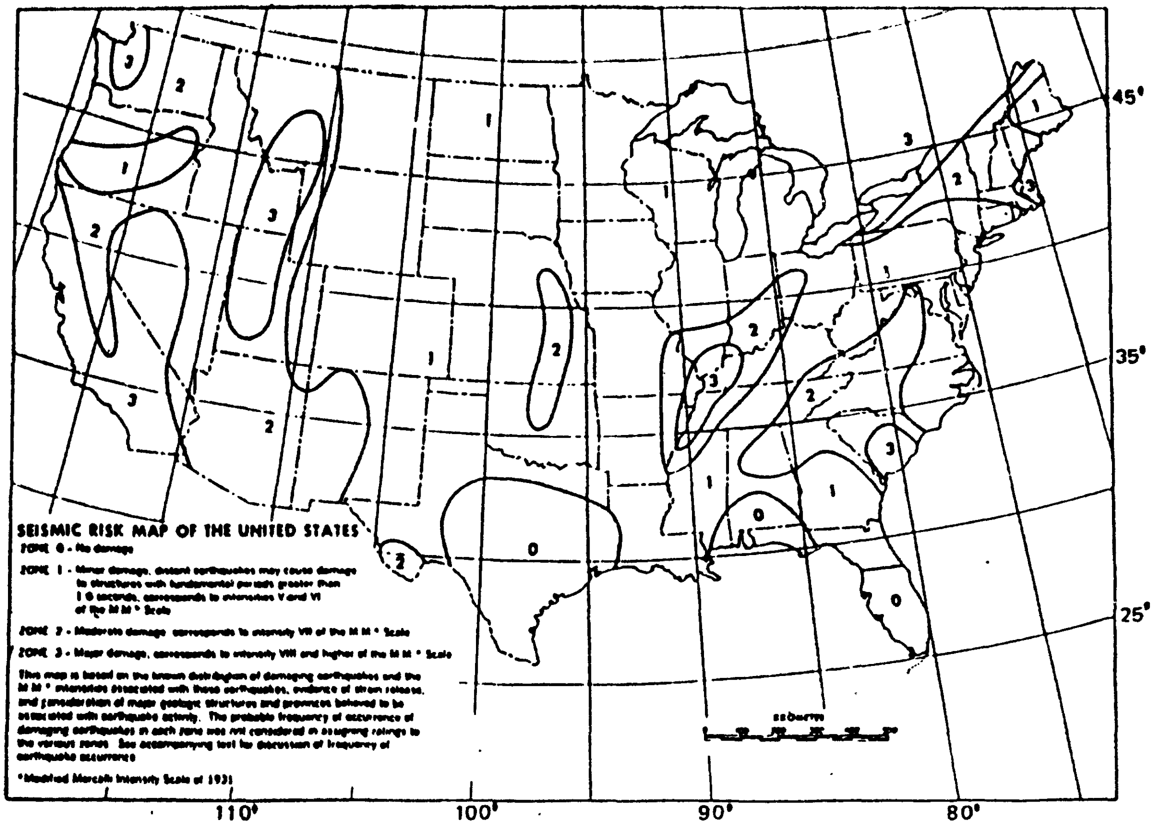

Figure 8. Seismic zoning map of the contiguous United States (Algermissen, 1969).

edition of the UBC, the Algermissen map was modified to include a zone 4 in a portion of California; and in 1979 and subsequent editions additional modifications were introduced. The introduction of the zone 4 in California had the effect qualitatively of taking into account the greater frequency of earthquakes of large magnitude that are possible in California.

Interest in the probabilistic estimation of ground motion increased in the 1960's as a result of the realization of the shortcomings of the existing hazard maps and because of the publication of a number of papers outlining possible probabilistic models and the application of these models to earthquake hazard estimation (for example, Lomnitz, 1966; 1969; Cornell, 1968; and Esteva, 1969).

A probabilistic acceleration map for the contiguous United States was published by Algermissen and Perkins in 1976 (fig. 9). The mapped quantity is the expected maximum acceleration in rock in a 50-year period with a 10 percent chance of being exceeded. A schematic diagram showing the elements in probabilistic hazard mapping is shown in figure 10. The concept of hazard mapping used in the preparation of the map is that earthquakes are randomly distributed in magnitude, interoccurrence time, and space. The occurrence distribution in space is uniform within source zones. Both the earthquake magnitudes and interoccurrence times have exponential distributions. Exponential interoccurrence times are characteristic of a Poisson process. The exponential magnitude distribution is an assumption based on empirical observation. The assumption of a Poisson process for earthquakes in times is consistent with historical earthquake occurrence insofar as it affects the probabilistic hazard calculation, provided the geographical areas considered are regional in nature. Large shocks closely approximate a Poisson process, but as magnitude decreases, earthquake occurrences may depart significantly from the Poisson model. However, ground motions associated with small earthquakes are of only marginal interest in engineering applications and consequently the Poisson assumption serves as a useful and simple model. Spatially, the seismicity is modeled by grouping it into discrete areas termed "seismic source zones." The two general requirements for a seismic source zone are that (1) it has seismicity, and (2) it is a reasonable seismotectonic or seismogenic structure or zone. If a seismogenic structure or zone cannot be identified, the seismic source zone is based on historical seismicity. A seismotectonic structure or zone is taken to mean a specific geologic feature or group of features that is known to be associated with the occurrence of earthquakes. A seismogenic structure or zone is taken to mean a geologic feature or group of features for which the style of deformation and tectonic setting are similar and a relationship between this deformation and historic earthquake activity can be inferred.

The development of probabilistic ground motion maps depends on a knowledge of the attenuation of ground motion from the seismic sources to any site where the probabilistic ground motion is to be calculated. Because of differences in seismic wave attenuation throughout the United States, it is important to use appropriate attenuation curves when suitable information is available. The accelerations mapped in figure 9 are average maximum accelerations in material having a shear wave velocity of about 0.75-0.90 km/sec. Because of the dispersion in attenuation data and because local site conditions can greatly modify levels of ground shaking, regional and national

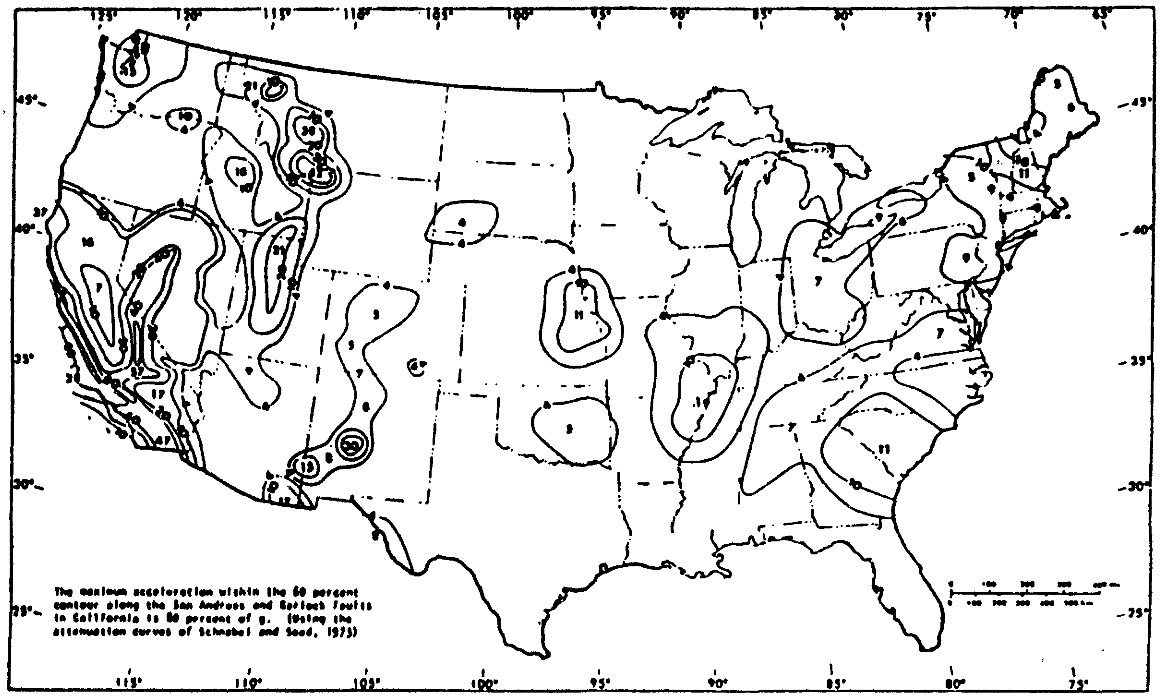

Figure 9. Probabilistic ground acceleration map of the conterminous United States, 50 year exposure time, 10 percent chance of exceedance. Contours are percent of g (Algermissen and Perkins, 1976). Compare the peak accelerations in the central United States with California. Note that the ratio of the peak values here are different than in Figure 11.

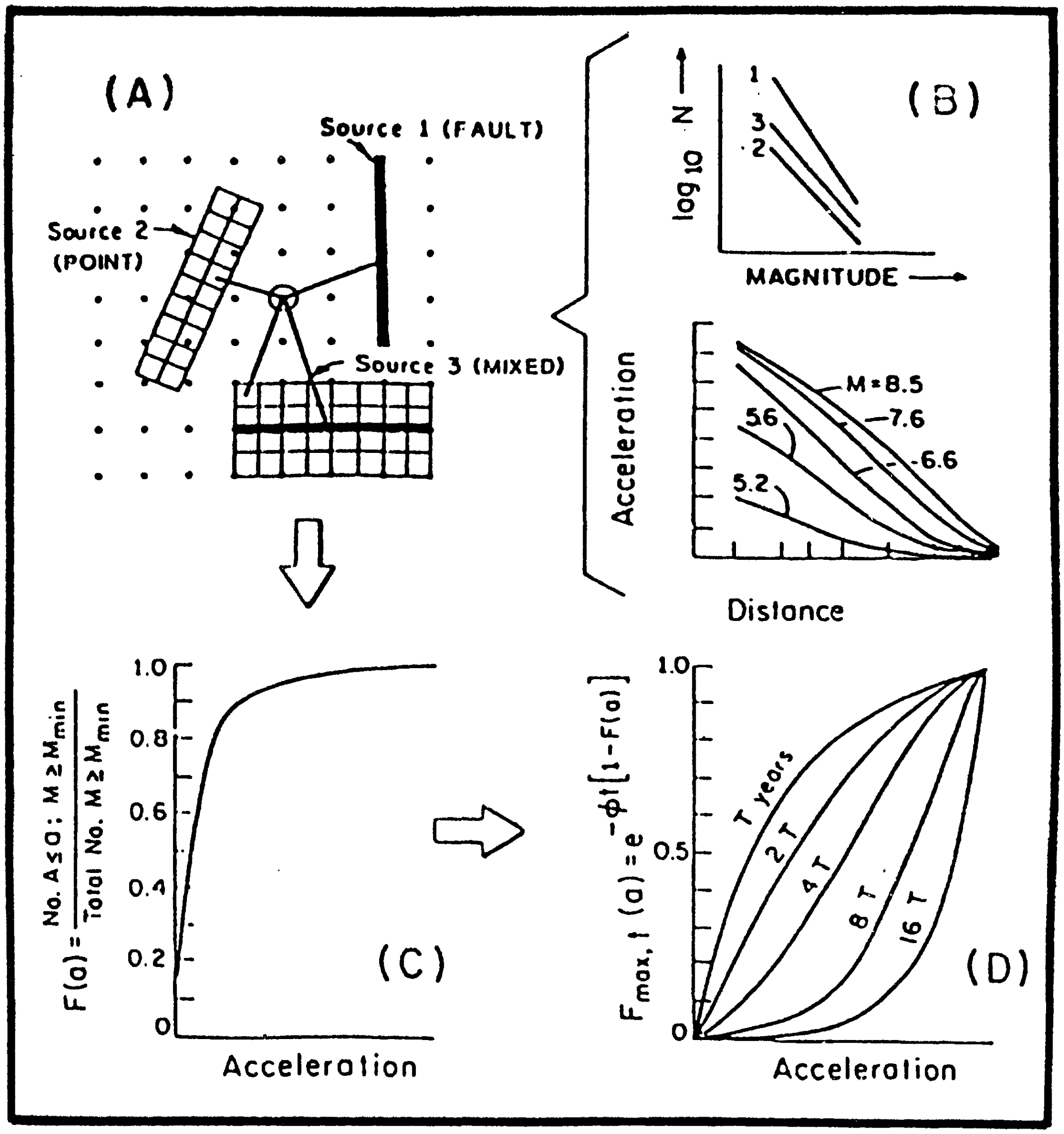

Figure 10. Elements of the probabilistic hazard calculations.

(A) Typical source areas and grid of points at which the hazard is to be computed.

(B) Statistical analysis of seismicity data and typical attenuation curves.

(C) Cumulative conditional probability distribution of acceleration.

(D) The extreme probability $F_{max,t}(a)$ for various acceleration and exposure time (T).

hazard maps of the type prepared by Algermissen and Perkins are most useful as guides on a regional basis to expected ground motion and for comparison of the seismic hazard in various areas. For specific locations of interest, local site response and geological conditions should always be evaluated. It is also useful to estimate the effect of parameter variability on the ground motion mapped. A number of interesting studies of the effects of parameter variability have been made (see, for example, Algermissen and others, 1982; McGuire and Shedlock, 1981).

Completion of the probabilistic acceleration map of Algermissen and Perkins (1976) coincided with the developmental phase of a project undertaken by the Applied Technology Council (ATC) that had as its aim the development of new nationally applicable seismic design provisions. The results of the Applied Technology Council study were published in 1978.

The ATC report contains two ground motion maps based on effective peak acceleration and effective peak velocity, which are used to obtain "design ground shaking" and, in turn, to compute lateral force coefficients. For the conterminous United States. These two maps are based on the map of estimated acceleration in rock in a 50-year period at the 90-percent probability level developed by Algermissen and Perkins (1976). The Algermissen-Perkins map is also contained in the ATC report. The ATC Effective Peak Acceleration map (fig. 11) is very similar to the Algermissen-Perkins acceleration map with the exception that the largest values of ground acceleration shown on the ATC map are 0.4 g in California, while the Algermissen-Perkins map has accelerations as high as 0.8 g in California. This implies that the probability of exceedance of 0.4 g is somewhat underestimated within the 0.4 g contours of the ATC map. The ATC Effective Peak Velocity map was derived from the Algermissen-Perkins acceleration map using principles and rules-of-thumb outlined in the report.

In 1982, Algermissen et al (1982) published probabilistic maximum acceleration and velocity maps of the conterminous United States for exposure times (periods of interest) of 10, 50, and 250 years. Parameter variability is also extensively discussed in the report accompanying the maps. The 50-year, 10 percent chance of exceedance acceleration map of the contiguous United States is shown in figures 12 through 17 for comparison with the 1976 Algermissen-Perkins (fig. 9). Considerable additional geological input was available for the delineation of seismic source zones used for the 1982 maps as compared with the source zones used for the 1976 map. This additional input resulted from a series of workshops held by the U.S. Geological Survey with invited regional experts from both within and outside the Survey (Thenhaus, 1983). Since ideas of the origins of seismicity, particularly in the central United States, may change considerably as a result of new research, ideas of and methods of delineating seismic source zones will also likely change in the future with a resulting change in the distributions of estimated ground motion. Maps such as those shown in figures 12 through 17 are important because they allow not only the estimation of ground acceleration and velocity but also spectral shape and building response. Figure 18 shows how a generalized type of building response spectrum can be obtained from estimates of peak acceleration, velocity, and displacement.

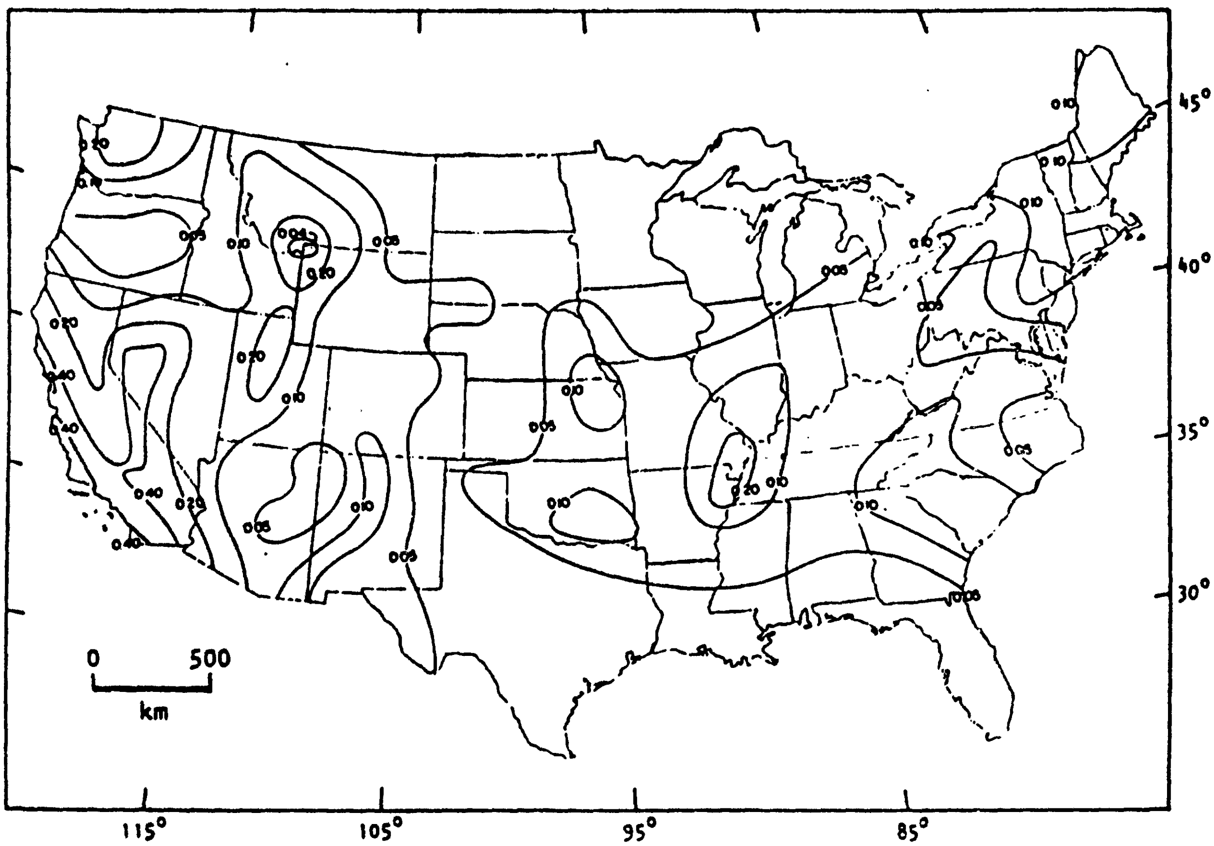

Figure 11. ATC effective acceleration map, Applied Technology Council, 1978.

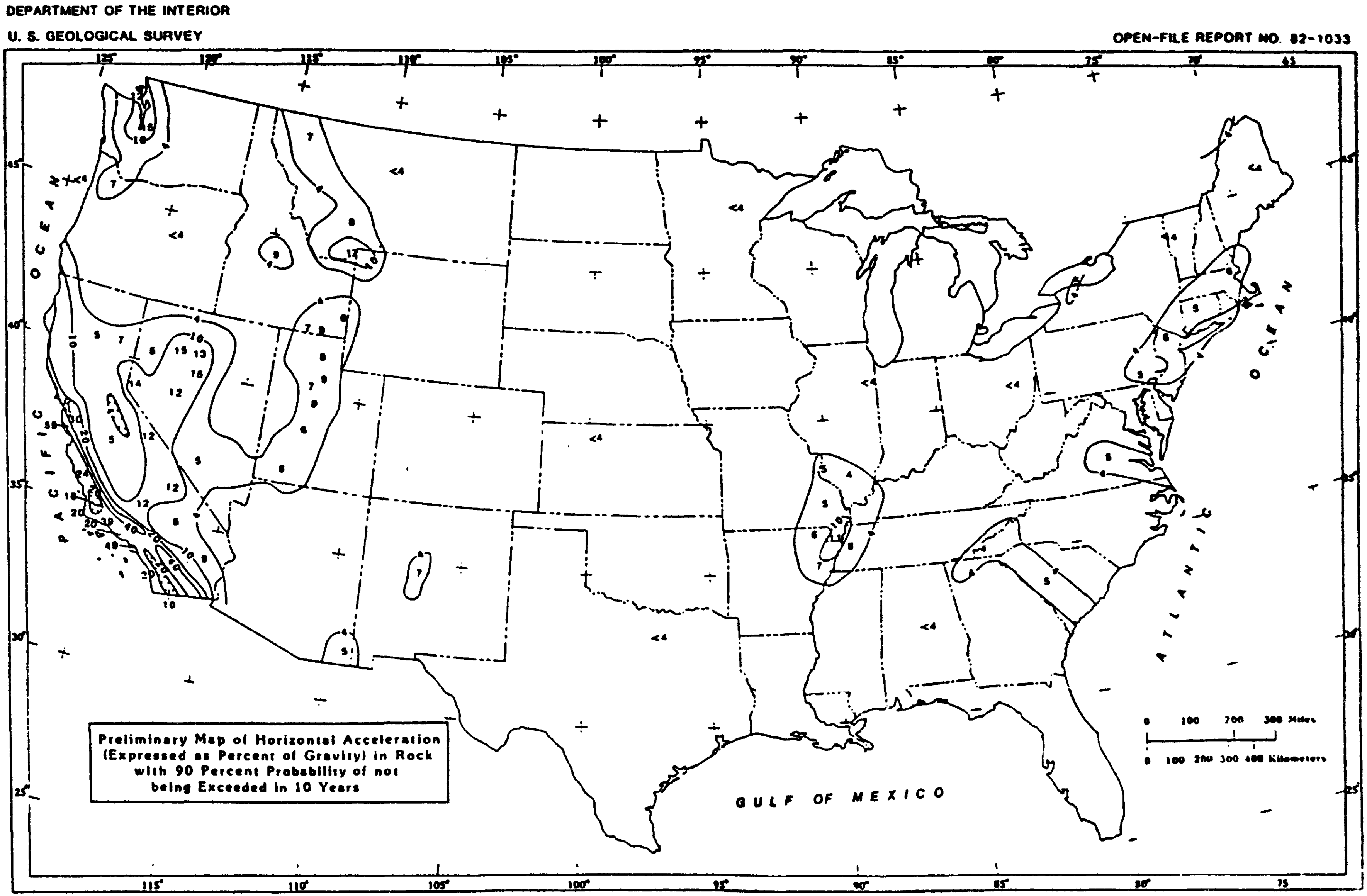

Figure 12. Ten year acceleration map.

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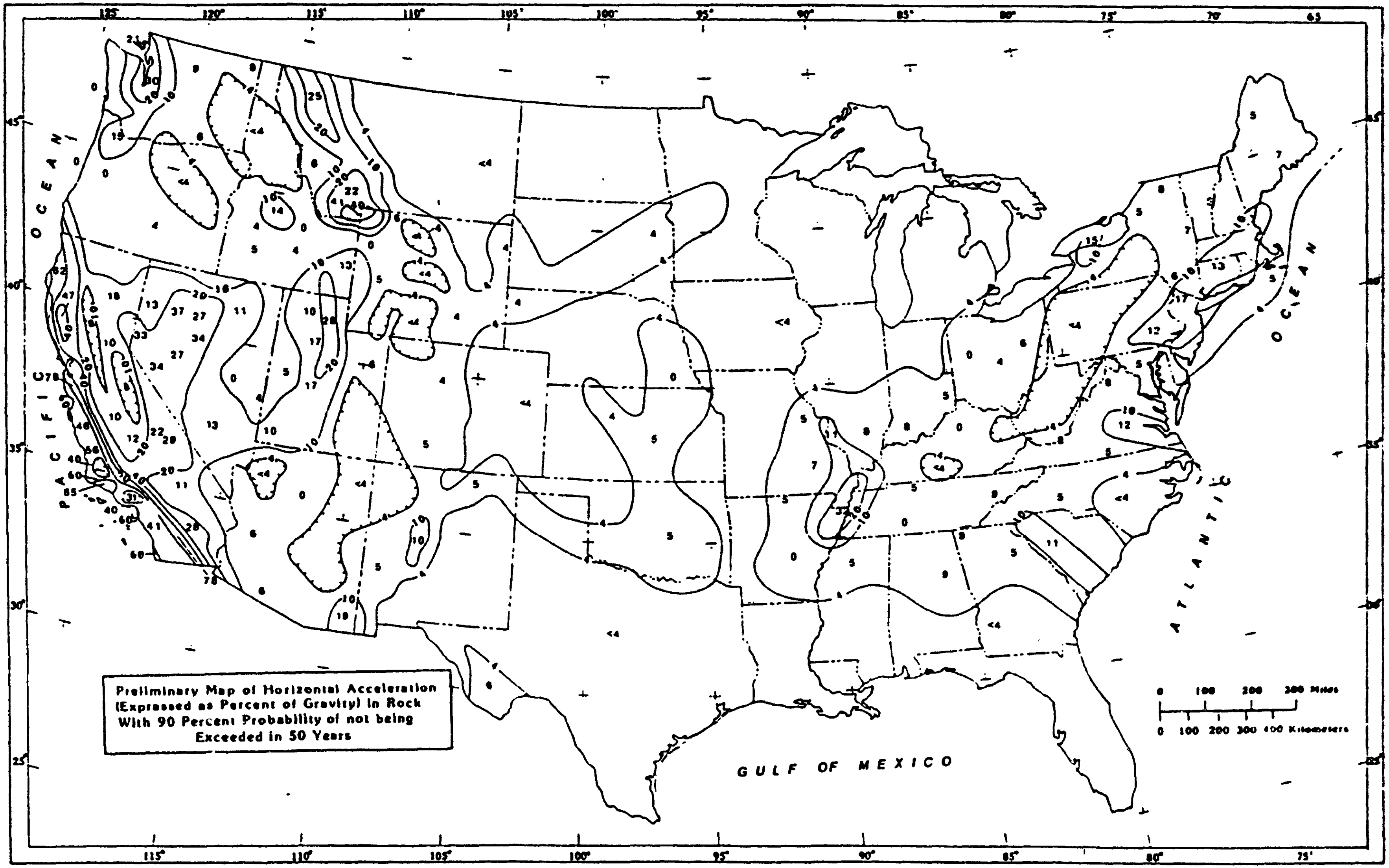

Figure 13. Fifty year acceleration map.

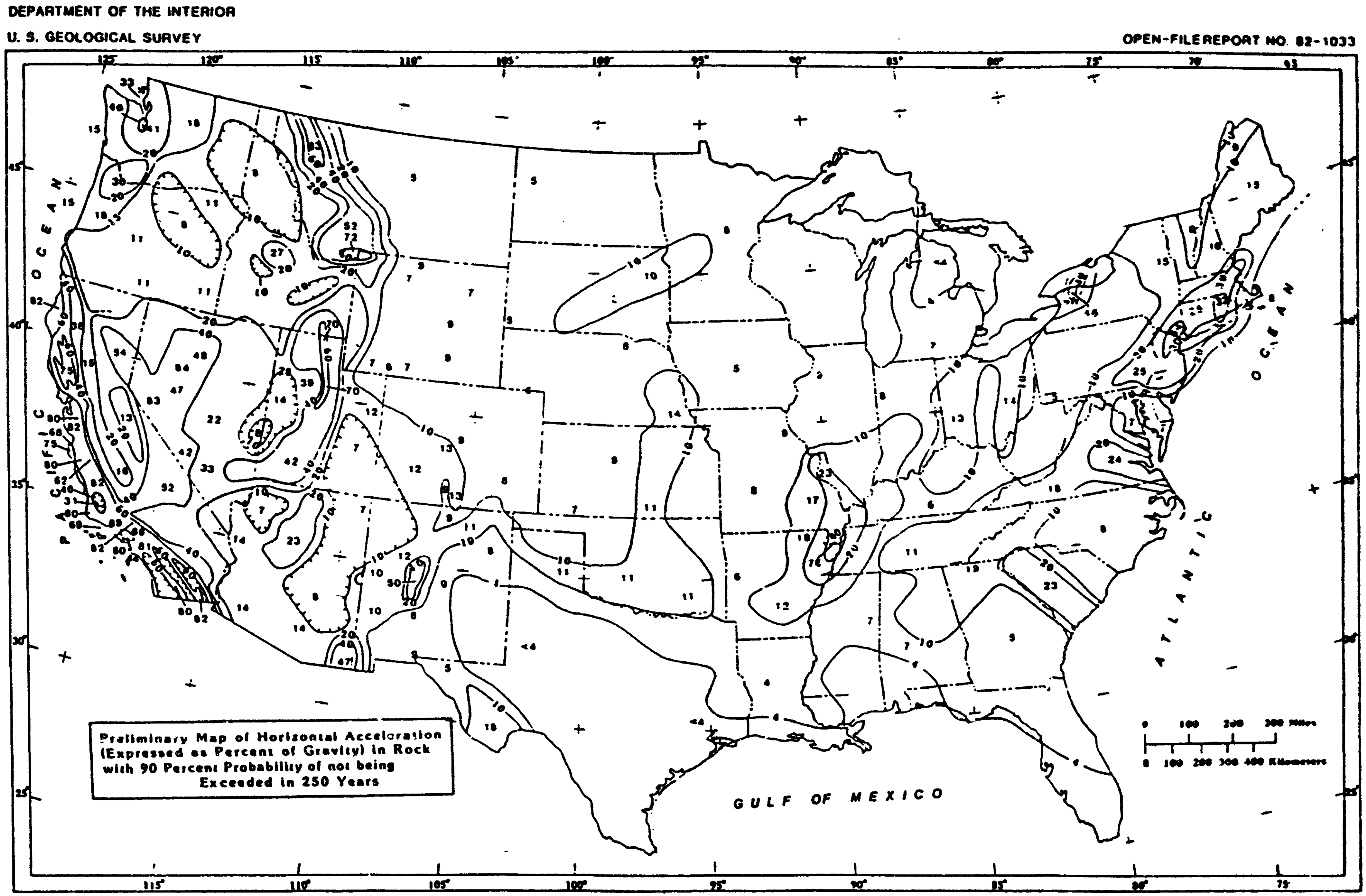

Figure 14. 250 year acceleration map.

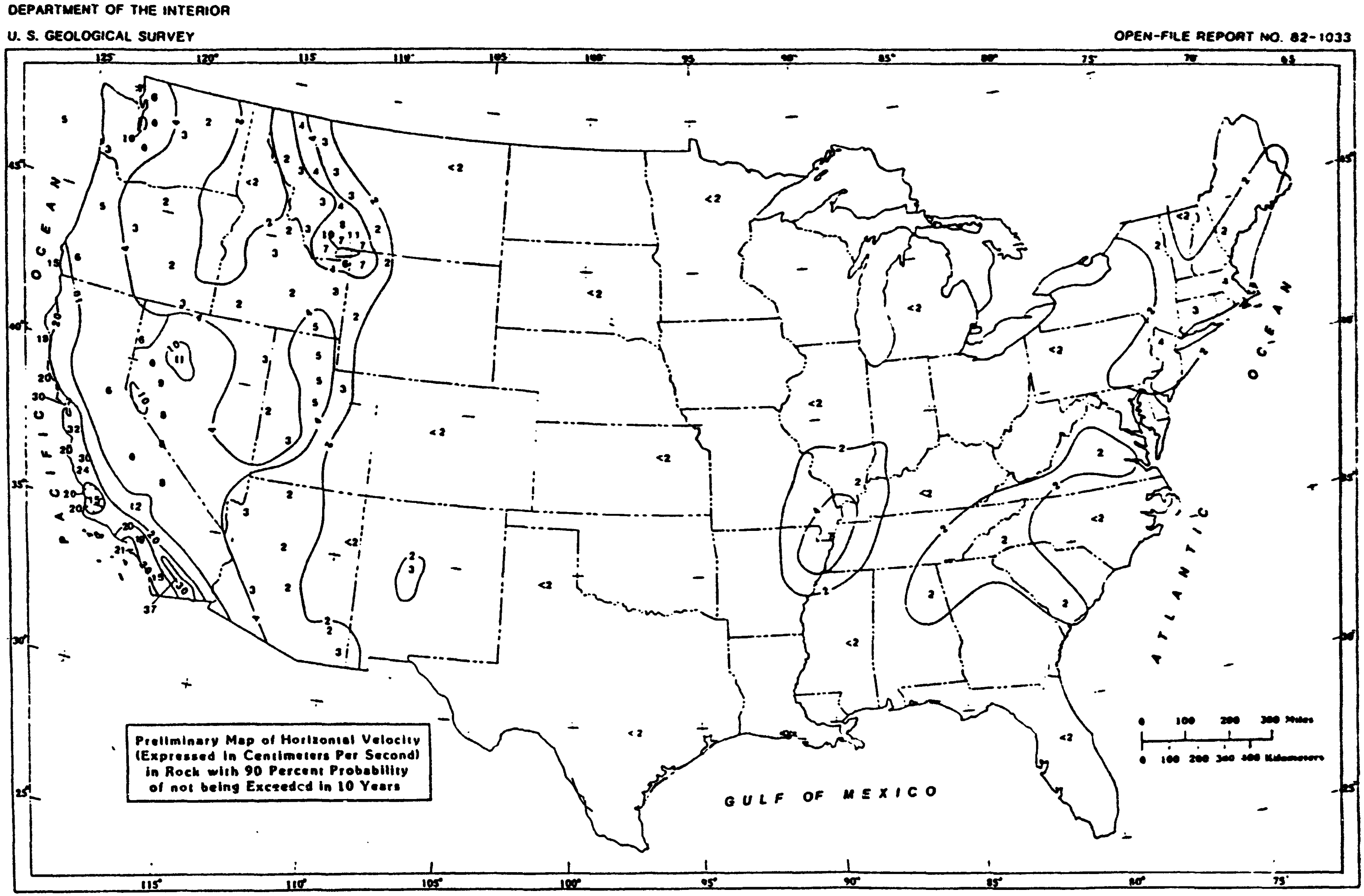

Figure 15. Ten year velocity map.

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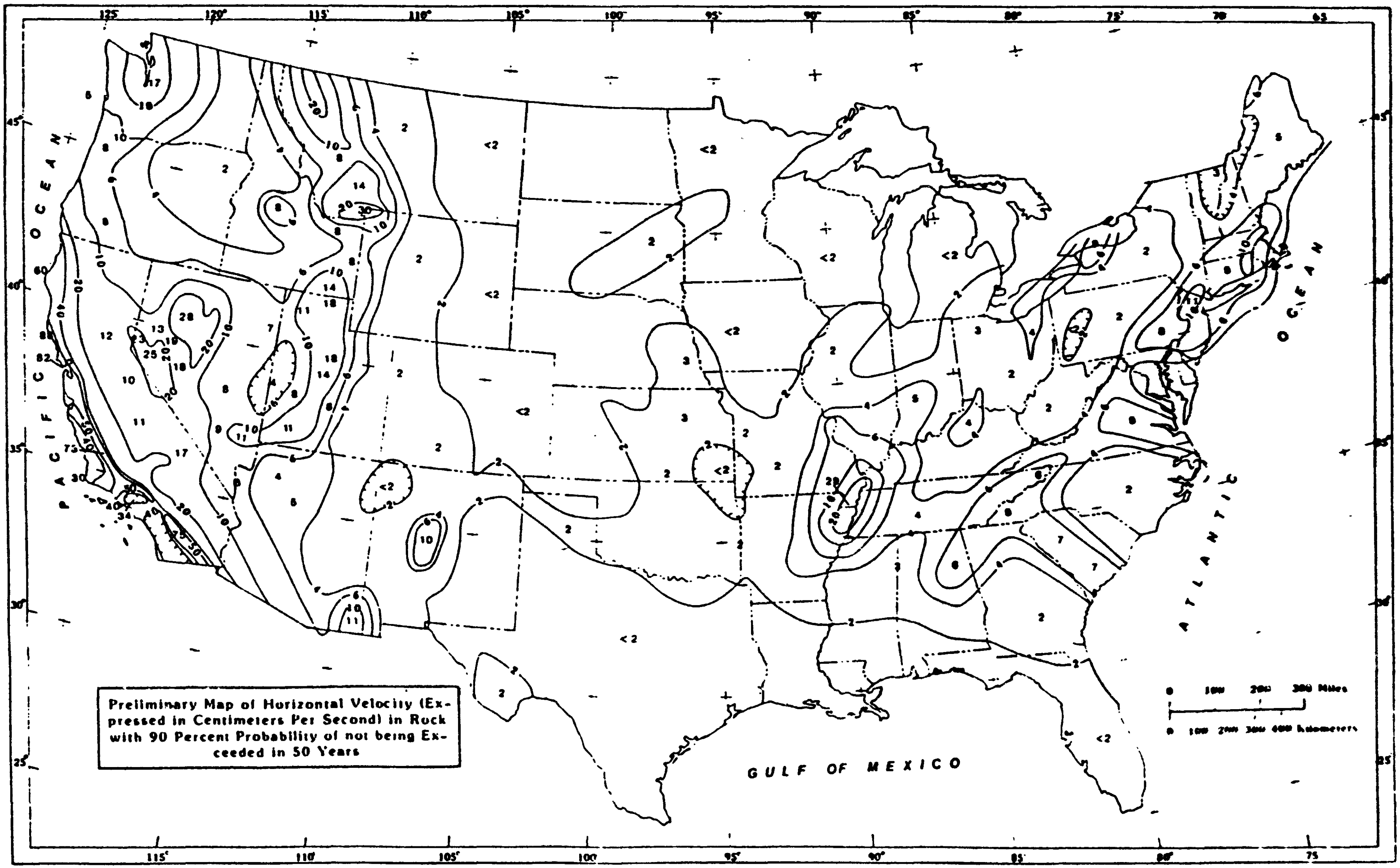


Figure 16. Fifty year velocity map.

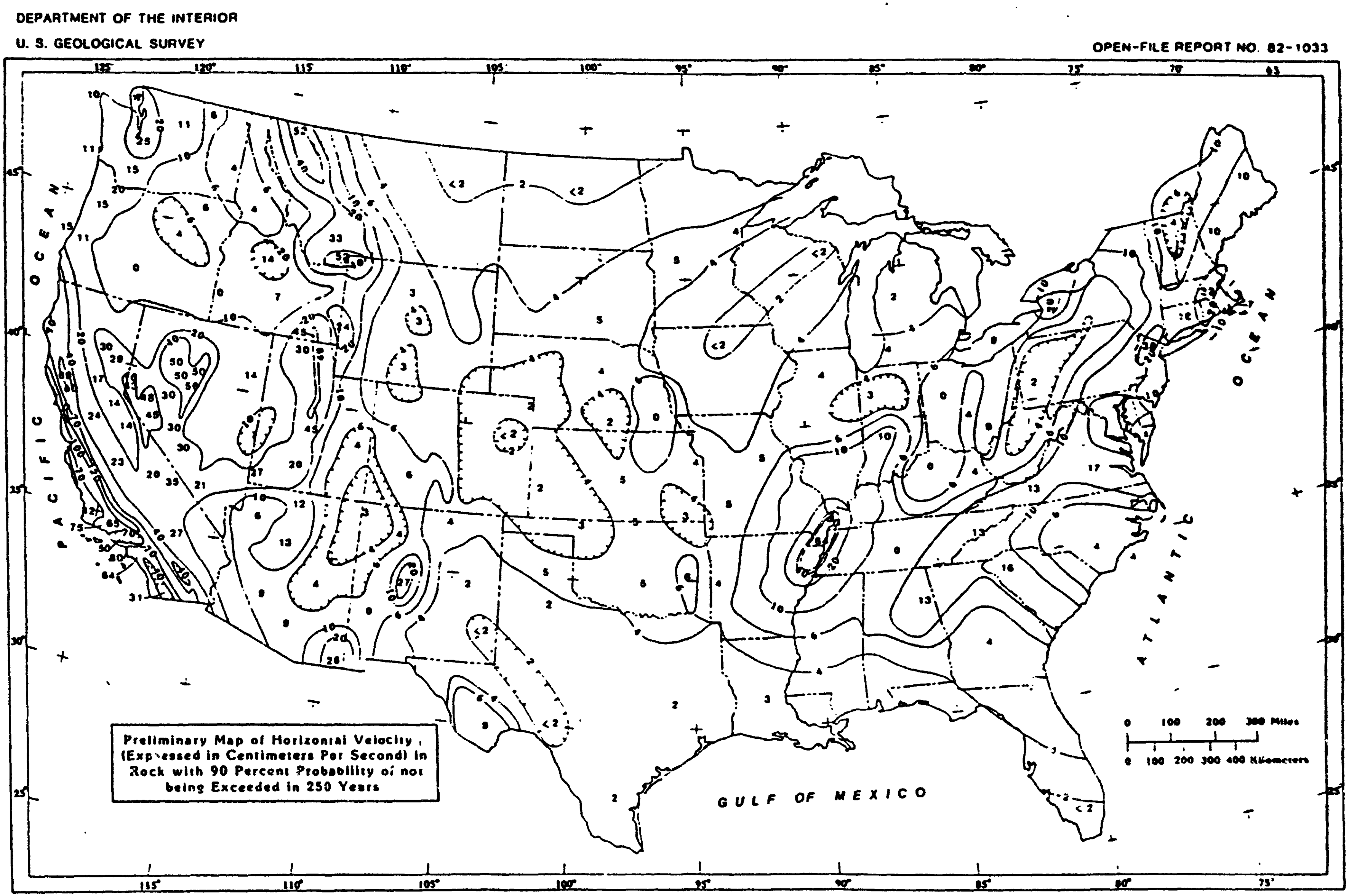
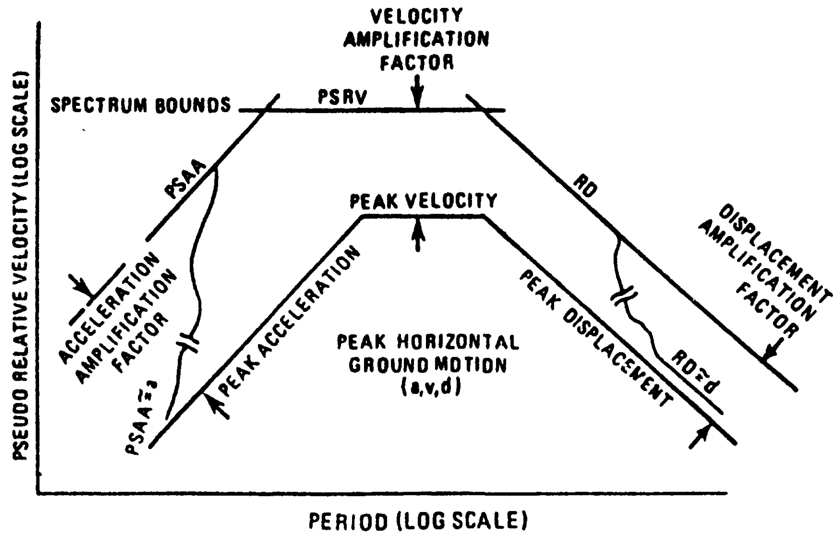


Figure 17. 250 year velocity map.



	AMPLIFICATION FACTOR		
DAMPING (percent)	ACCELERATION	VELOCITY	DISPLACEMENT
0	6.4	4.0	2.5
0.5	5.8	3.6	2.2
1	5.2	3.2	2.0
2	4.3	2.8	2.0
5	2.6	1.9	1.8
7	1.9	1.5	1.4
10	1.5	1.3	1.2
20	1.2	1.1	1.0

Figure 18. Schematic illustration of technique for developing site-independent response spectra (modified from Newmark and Hall, 1969). The quantities a, v, and d refer to the peak ground acceleration, velocity, and displacement; PSAA, PSRV, and RD refer to the spectral acceleration, velocity, and displacement (from Hays, 1980).

Figure 19 shows the seismic source zones in the midwest used in the development of the 1982 probabilistic ground motion maps, and figure 20 shows the seismic source zones of the New Madrid Seismic Zone and surrounding zones with the historical seismicity superimposed (taken from figure 2).

The U.S. Geological Survey is currently working on a new generation of probabilistic ground-motion maps that will make use of the best, recent regional ground-motion attenuation relationship available. In addition, maps will be prepared that will make it possible to estimate not only the amplitude of the ground motion throughout the country but also the frequency content, or spectrum of ground motion throughout the United States.

Figure 21 shows a comparison of the expected peak accelerations at various locations throughout the United States for various time periods of interest. This type of presentation is a convenient way to compare the relative earthquake hazard throughout the country.

EARTHQUAKE RISK (LOSS) STUDIES

Introduction

The assessment of possible earthquake losses is an important aspect of the earthquake problem. Assessment of losses permits the efficient organization of earthquake loss mitigation efforts. Earthquake assessments are critical to disaster preparedness, improved seismic provisions of building codes, improved land-use planning, and priorities in research programs.

From the discussions in the preceding sections of this paper, it is clear that there have been a number of moderately damaging earthquakes in the central United States and that the area has the potential for catastrophic losses should the earthquake series of 1811-12 or a similar sequence recur. This leads to two measures of earthquake risk that are of particular interest.

1. Average annual loss per structure (or per area).

2. Catastrophe potential - many losses resulting from a single event (a measure of variability of the risk).

The relative importance of the average annual loss as compared with the catastrophe potential varies with the nature of the earthquake hazard. For example, the average annual loss measured by the earthquakes that have occurred in the past 100 years in the southeast Missouri portion of the Mississippi Valley is small but the catastrophe potential (in the event of a recurrence of four large earthquakes such as occurred in 1811-1812) is great. The average annual loss in the Imperial Valley of California is significant while the catastrophe potential is perhaps somewhat less than in the Mississippi Valley. This is based on the fact that while numerous damaging earthquakes (up to M_s 7.3) have occurred, no great earthquakes (M>8) have occurred historically in the Imperial Valley.

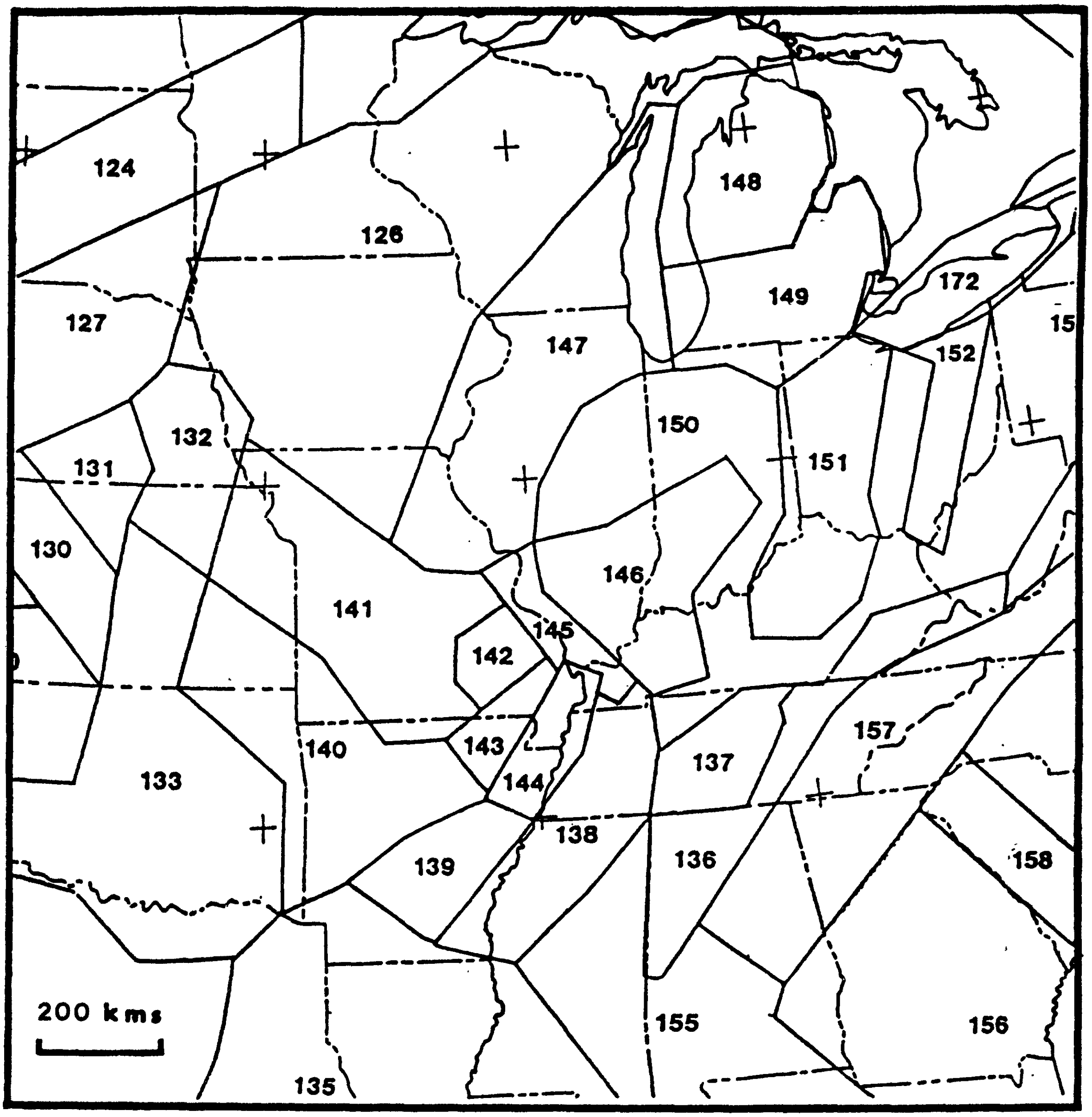


Figure 19. Seismic source zones used in the development of the 1982 ground motion maps of the United States (Algermissen and others, 1982).

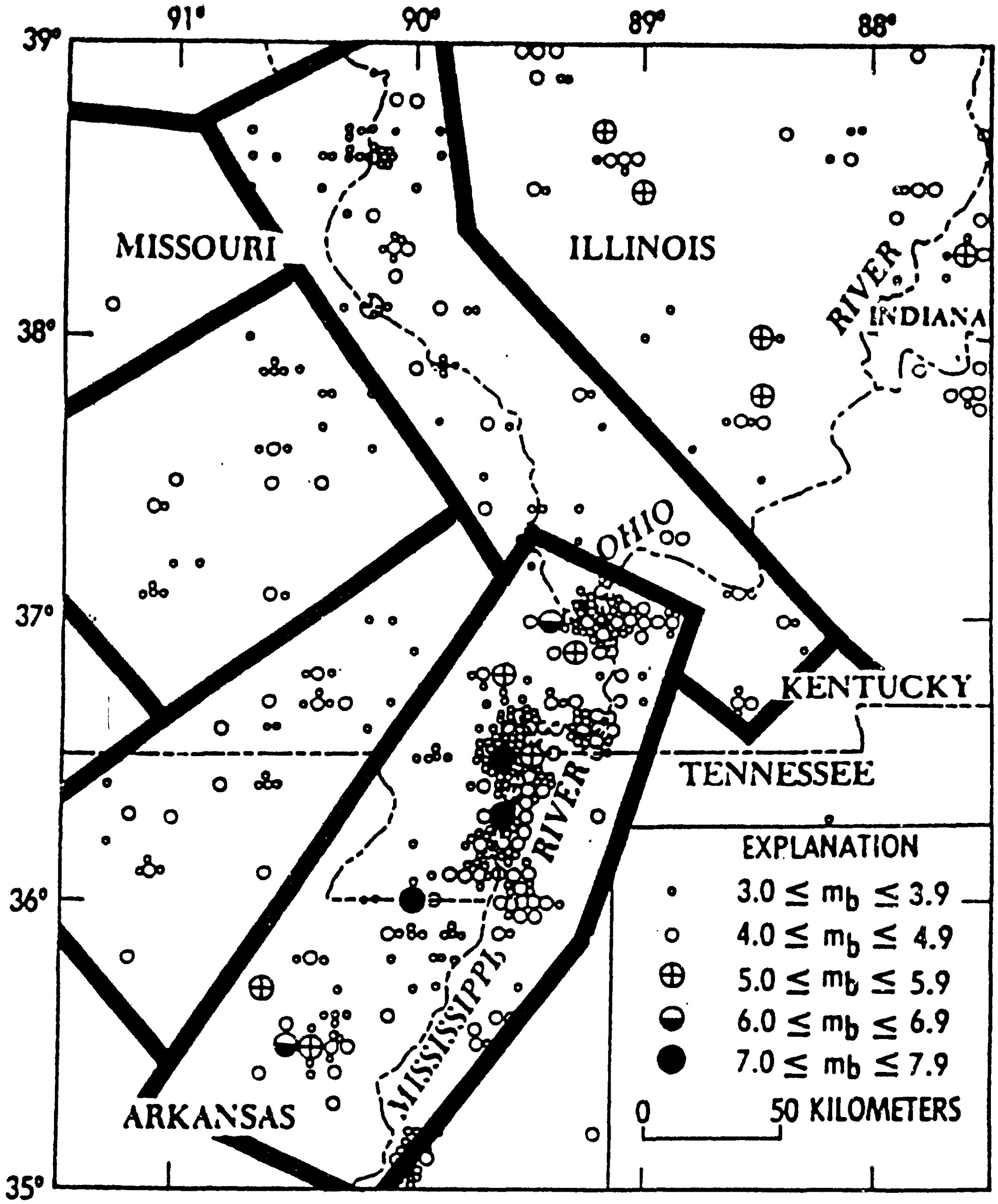


Figure 20. Detail of seismic source zones in the Mississippi valley (from figure 19) together with the historical seismicity (from figure 2).

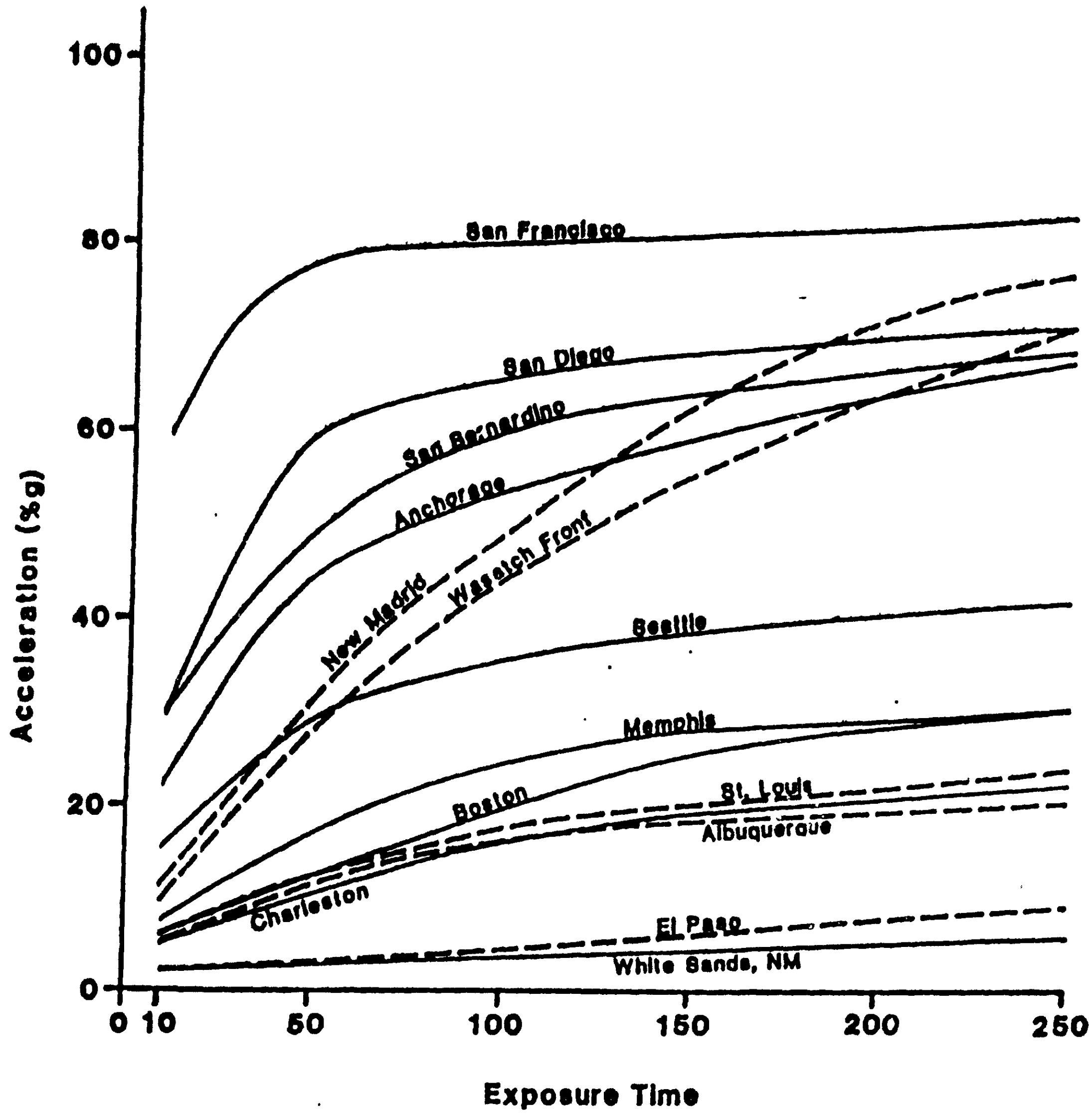


Figure 21. Comparison of the maximum expected ground acceleration in 10, 50 and 250 years at a number of sites in the United States. These data were derived from the maps in figures 12 through 14. The ground accelerations shown have a 10 percent chance of being exceeded in the time periods shown.

How can average annual loss and catastrophe potential be determined? First, it is necessary to identify the elements in seismic risk analysis. These elements--inventory, vulnerability, and hazard assessment are shown in figure 22.

Inventory

The development of a suitable inventory of structures and other facilities (such as lifelines) at risk is an essential component of any loss study and is, in many ways, the most difficult aspect of risk assessment to resolve. The U.S. Geological Survey in its risk studies has used some of the following approaches:

Dwellings: The Bureau of the Census provides adequate data for the distribution and number of residential housing in the United States but not framing system and construction materials. These later characteristics must be determined by statistical sampling.

Buildings other than dwellings: A number of techniques have been used to develop non-dwelling inventory, such as the following:

1. Zoning and land-use classification maps.
2. Building and permits and assessor's records.
3. Commercial building surveys (such as the now obsolete Sanborn maps, various commercial summaries of building statistics, etc.)
4. Local building departments.
5. Industry groups, regulatory agencies and owners (for lifelines).
6. Statistical sampling.

All of the above sources of inventory provide incomplete data that must be supplemented by sampling. The amount and detail of the sampling possible in any particular risk assessment depend upon the amount of resources available for the assessment.

Vulnerability

Vulnerability is the susceptibility of a component of a structure, or class of structures, to damage. Vulnerability is often expressed as the percent of the total replacement cost of a structure required to repair it when it is subjected to some specified type and severity of earthquake hazard. The earthquake hazard may be ground shaking, landsliding, liquefaction, tsunami wave, etc.

Vulnerability is essentially the linkage between hazard and loss and is obviously critical to risk assessment. Unfortunately, the data base for vulnerability is very poor. There are a number of reasons for this state of affairs. First, the characteristics of the building stock at risk have changed over the years and is constantly changing as new building and other structures are completed and older ones demolished. Thus, there is always little damage experience for new building designs and materials. Second, there is the problem of what actually is the loss when an older structure is damaged or destroyed. How should it be repaired or replaced? Third, damage information from many earthquakes is sketchy and only qualitative in nature.

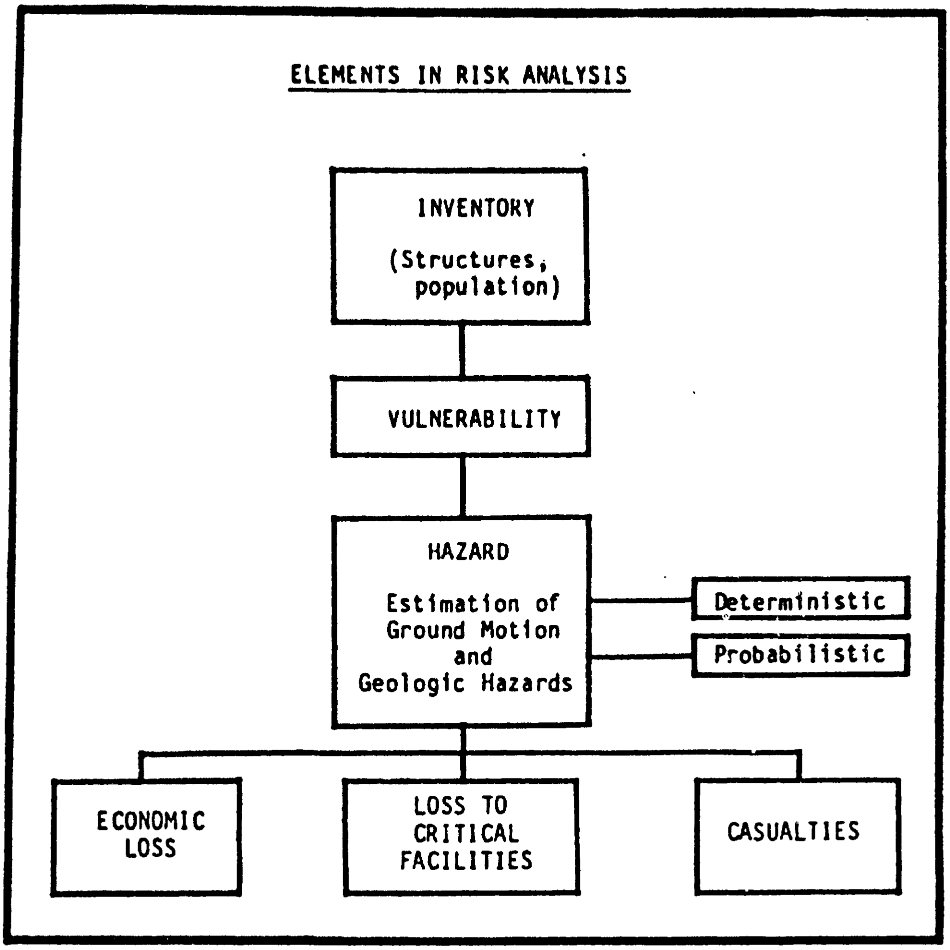


Figure 22. Elements in seismic risk analysis.

Data are rarely available in the context of the total building stock at risk. In particular, it has been the practice in post-earthquake damage surveys to intensively investigate a few structures of engineering interest while subtle damage to large numbers of structures is ignored. Only very recently have earthquake damage surveys attempted to be quantitative in context and statistically designed. Fourth, post-earthquake damage surveys are expensive and time consuming if these surveys are to meet the needs of future damage (risk) assessment. Examples of vulnerability relationships for California are those developed by K.V. Steinbrugge for the Insurance Services Office (ISO). These are shown in figure 23 and the building classes are described in table 2 (Algermissen and Steinbrugge, 1984). Vulnerability relationships have also been published by the Applied Technology Council (1985) and a number of other groups. Note that in figure 23, percent damage is shown as a function of Modified Mercalli intensity. This has been the traditional way to present vulnerability information. A more direct and satisfactory method of assessing vulnerability (and loss) would be to analyze directly, the damage (for example, present replacement cost) by class of construction with distance from the macroseismic center of earthquake effects. This approach has been suggested by Steinbrugge, Algermissen, and Lagorio (1984).

Hazard Assessment

The earthquake hazard assessment used in risk analyses may be either deterministic or probabilistic. An example of a deterministic hazard assessment is shown in figure 24 (Algermissen and Hopper, 1984), which is essentially a simulation of the earthquake ground shaking (in terms of Modified Mercalli intensity) in the event of a recurrence of the 1811-12 sequence in the New Madrid Seismic Zone. This intensity map was derived from the data in figure 4 (Nuttli, 1981) and from studies of the 1843 shock (Hopper and others, 1985) at the south end of the New Madrid Seismic Zone and the 1895 shock (Hopper and Algermissen, 1980) at the north end of the zone. Convolving this intensity data with the appropriate vulnerability relationships (for example, figure 23) and inventory provides an assessment of catastrophe potential in the central United States.

Probabilistic ground motion maps as previously discussed, provide all of the data necessary to estimate both average annual loss and catastrophe potential, either explicitly, as a result of the probabilistic assessment, or implicitly, as part of the computational process. For example, the ground motion associated with a catastrophic loss is approached when long exposure times and low probabilities of exceedance are used. The probabilistic ground motion assessment should normally be in terms of Modified Mercalli intensity (as illustrated in figure 25) rather than ground acceleration to facilitate the use of vulnerability relationships, such as those shown in figure 23.

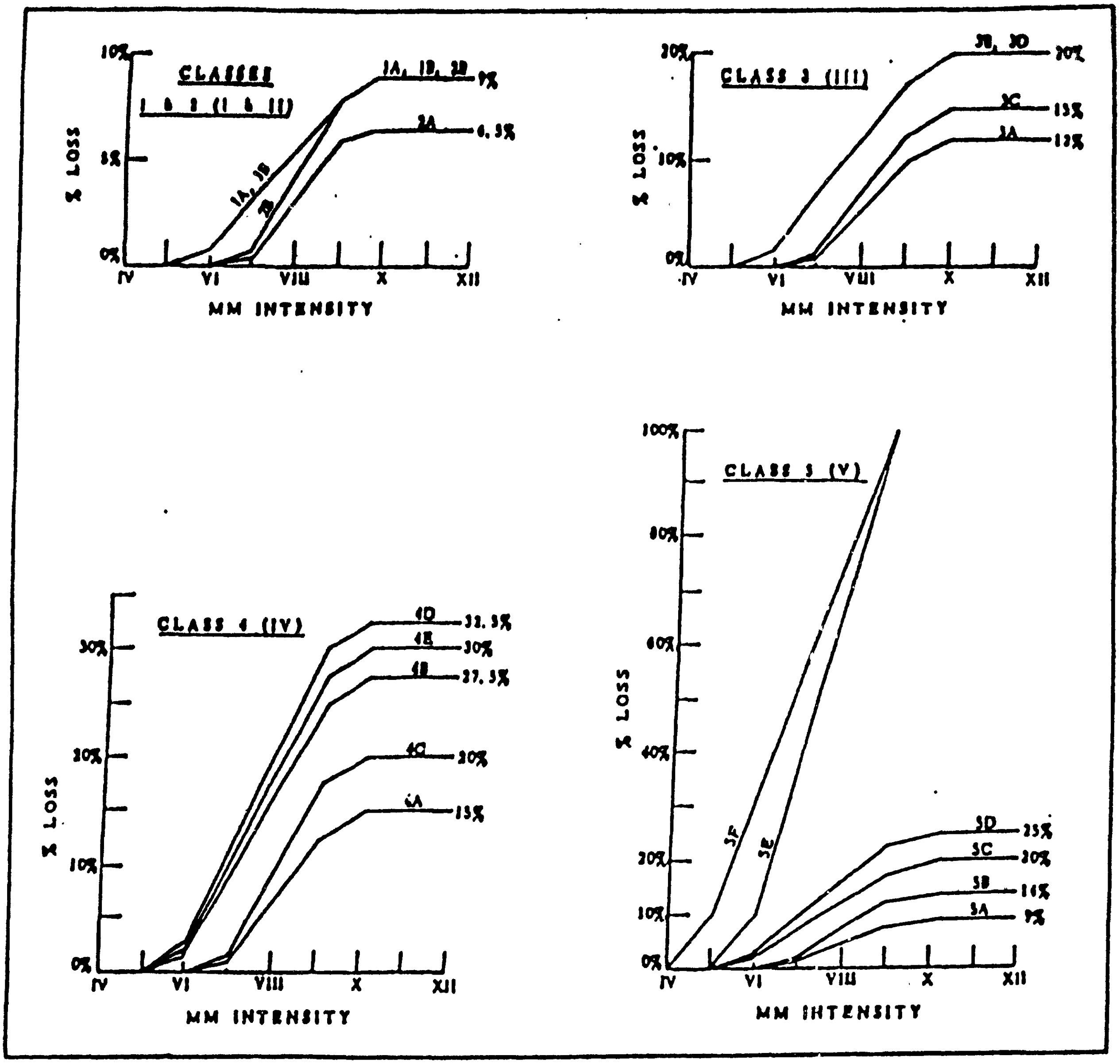


Figure 23. Vulnerability relationships (K.V. Steinbrugge, 1986) for the classes of construction in table 2.

Table 2. Notation used to identify building classes and brief description of building classes

Building Class	Brief description of building subclasses
1A	Wood frame and stuccoed frame dwellings regardless of area and height Wood frame and stuccoed frame buildings, other than dwellings, which do not exceed 3 stories in height and do not exceed 3,000 square feet in ground floor area Wood frame and stuccoed frame structures which do not exceed 3 stories in height regardless of area
1B	Wood frame and stuccoed frame buildings not qualifying under class 1A
2A	One story all metal; floor area less than 20,000 ft^2
2B	All metal buildings not under 2A
3A	Steel frame, superior damage control features
3B	Steel frame, ordinary damage control features
3C	Steel frame, intermediate damage control features (between 3A and 3B)
3D	Steel frame, floors and roofs not concrete
4A	Reinforced concrete, superior damage control features
4B	Reinforced concrete, ordinary damage control features
4C	Reinforced concrete, intermediate damage control features (between 4A and 4B)
4D	Reinforced concrete, precast reinforced concrete, lift slab
4E	Reinforced concrete, floors and roofs not concrete
5A	Mixed construction, small buildings and dwellings
5B	Mixed construction, superior damage control features
5C	Mixed construction, ordinary damage control features
5D	Mixed construction, intermediate damage control features
5E	Mixed construction, unreinforced masonry
6	Buildings specifically designed to be earthquake resistant

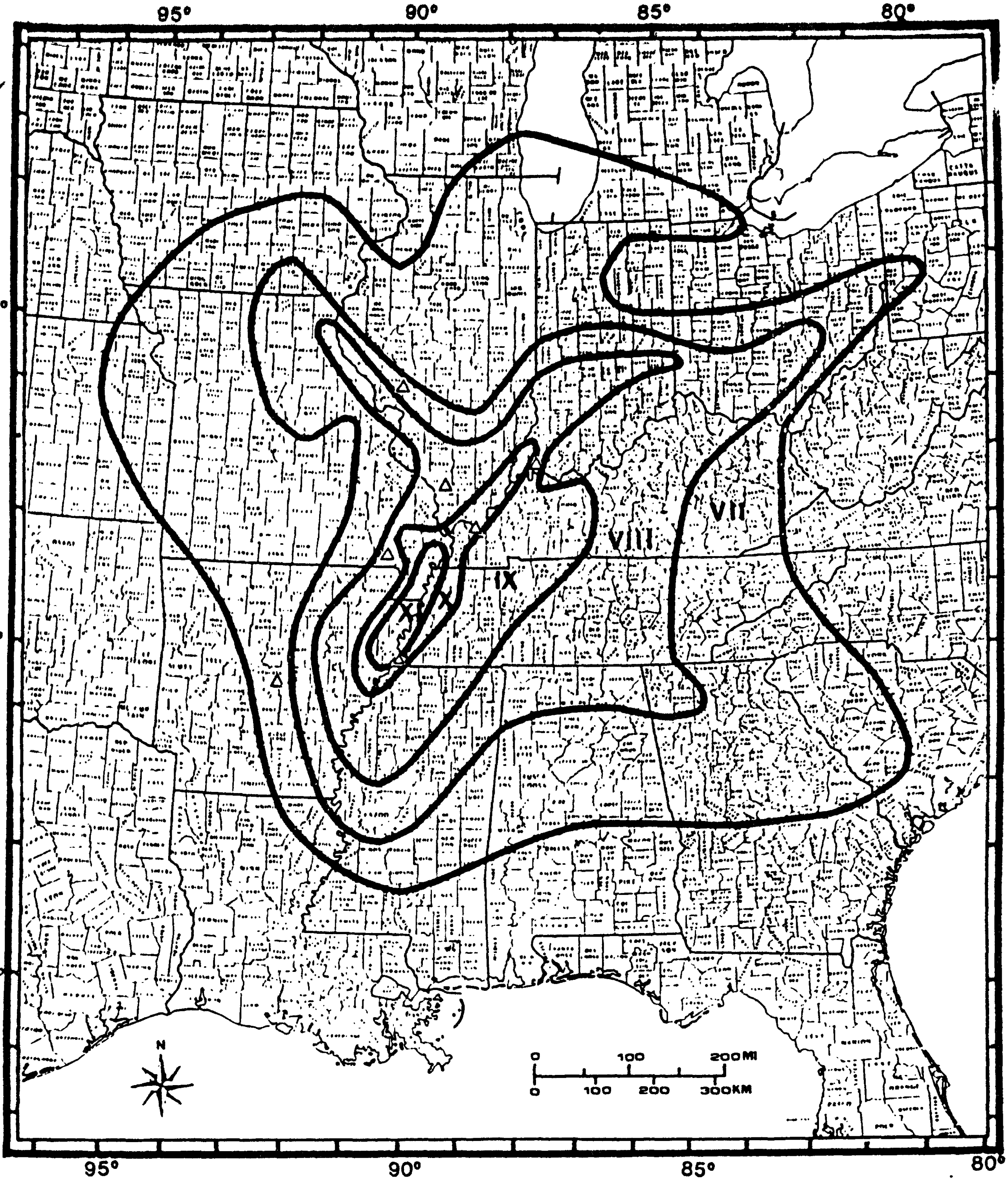


Figure 24. Simulated isoseismal map showing the estimated distribution of estimated maximum Modified Mercalli intensities in the event of a recurrence of the 1811-12 sequence of earthquakes in the Mississippi valley.

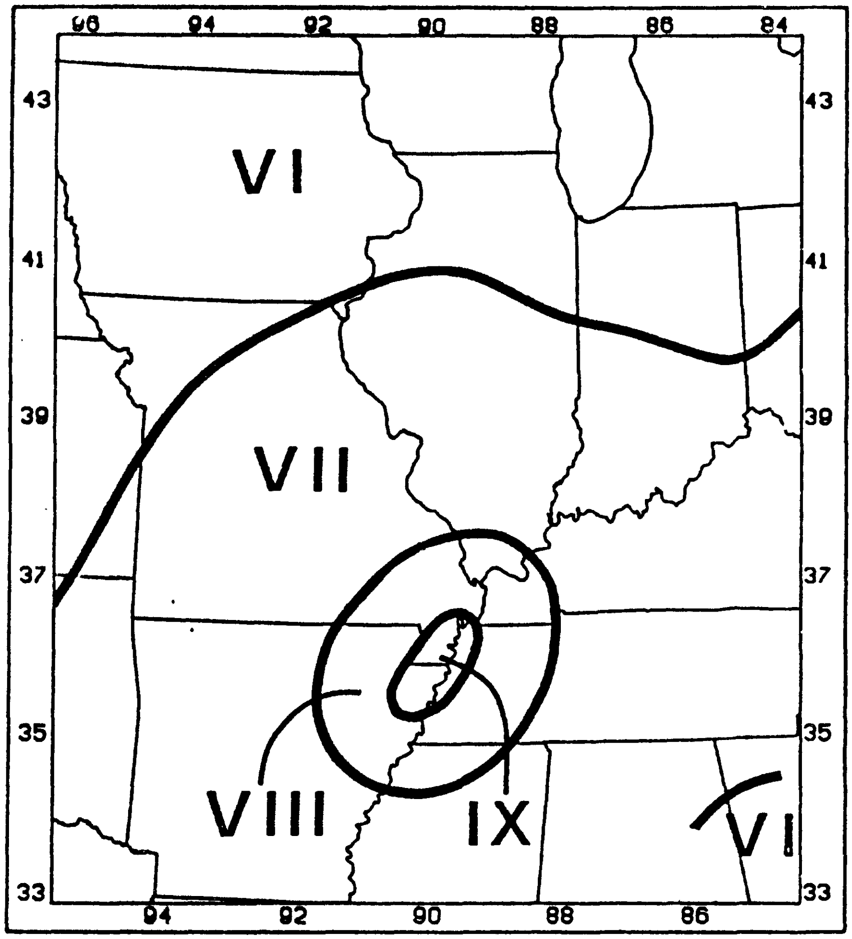


Figure 25. Modified Mercalli intensity with a 10 percent chance of being exceeded in 50 years.

As an example of hazard assessment that can be used to make a loss estimate that is neither an average annual loss nor an estimate of catastrophe potential, consider the hazard assessment in figure 25. Figure 25 shows, in a general way, the expected maximum ground motion in 50 years with a 10 percent chance of exceedance in terms of Modified Mercalli intensity. Considering only losses to dwellings in areas of intensity VIII and greater and convolving these intensity values (by county) with appropriate vulnerability relationships (such as those shown in figure 23) and an appropriate dwelling inventory at risk suggests a 50 year, 10 percent chance of exceedance dwelling loss of about 8.0 billion in 1980 dollars.

SUMMARY

An attempt has been made to outline the most important seismological and seismotectonic elements critical to earthquake hazard assessment in the central United States. The historical development of seismic zoning efforts in the region has also been presented. Finally, the elements of earthquake loss assessment are introduced together with the application of seismic risk (loss) techniques to the central United States.

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AN 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

Central United States Earthquake Preparedness Project

October 1985

(prepared under contract # EMK-C-0057)

F O R

E M E R G E N C Y   R E S P O N S E   P L A N N I N G

P U R P O S E S

O N L Y

The primary purpose of this report is to assist emergency managers and planners in the development of response plans to deal with the consequences of major earthquakes in the central United States. This report is not intended for any other use.

In particular, the probabilistic methods which underlie the estimation of damage to structures and the resulting casualties, were developed and applied to yield such estimates only for groupings or aggregations of structures of similar types or purpose. For the level of analysis performed for this report, these techniques were not intended to provide damage descriptions for individual structures. No attempt should be made to use the findings of this report for other than the above stated purpose.

EXECUTIVE SUMMARY

I - General

The Central United States Earthquake Preparedness Project (CUSEPP) is an on-going effort to reduce the hazards associated with earthquakes through determination of the potential consequences of major earthquake events in the New Madrid Seismic Zone, an increase of the awareness of those consequences among public officials and the private sector, the development of response plans for coping with them, and the implementation of actions for reducing them. This report, supported by estimates of ground shaking developed by the U.S. Geological Survey, provides preliminary estimates of the potential consequences of two major sizes of earthquakes in six cities within or near the seismic zone. These cities are: Little Rock, Arkansas; Carbondale, Illinois; Evansville, Indiana; Paducah, Kentucky; Poplar Bluff, Missouri; and Memphis, Tennessee. The cities were chosen on the basis of several factors: 1) population size in relation to the preliminarily identified areas of damage intensities, 2) architectural types and, 3) cooperative environment of the city to be studied. Only those parts of the urbanized area actually within the designated corporate limits of each city were surveyed and studied.

The earthquake effects studied are based upon the ground shaking estimates of two sizes of events, having surface magnitudes (Ms) of 7.6 and 8.6. The reader will note that the effects on the six cities combined are maximized since the estimate of ground shaking assumes that the epicenter of each earthquake scenario is located as close to each city as possible within the entire New Madrid Seismic Zone. The

Ms=8.6 event allows assessment of the upper limits of damage and needs. The 7.6 earthquake represents an event with a greater probability of occurrence, and can be viewed as more appropriate for realistic risk assessment and subsequent emergency management measures.

The selection of these magnitude events for CUSEPP planning is reasonable from at least two points of view. First, such earthquakes have actually occurred in this region; each of the "great" earthquakes of 1811 and 1812, which are widely referenced in earthquake literature, had surface magnitudes above 8.0 on the Richter Scale and approximate the size of the larger (Ms=8.6) earthquake. The 1811-1812 series also included hundreds of aftershocks, many with magnitudes estimated to be between 6.5 and 7.6. Second, recent earthquake research has theorized that current strain in the New Madrid Seismic Zone would create a Ms=7.6 earthquake if it were all released today and, further, that the probability for the occurrence of such an event during the life span of existing and planned structures and the lifetime of persons now living does exist.

The occurrence of either Ms=8.6 or Ms=7.6 earthquakes would result in damages, disruption, casualties, and injuries on a scale never experienced from a natural hazard in the history of this nation; the immediate and long term relief and recovery efforts would place a significant, prolonged burden upon the regional and national economy.

Of equal, if not greater importance is the fact that earthquakes of lesser, yet significant, power are much more likely to occur.

Moderate sized earthquakes are a very real hazard for the CUSEPP planning area. The serious (though localized) damage in Coalinga, California which resulted from the May 2, 1983 event (6.5 on the Richter Scale), demonstrates the damage which can be caused to an area by a moderate earthquake that does not have a high level of seismic design in construction. Due to the different soil conditions and overall lack of adequate seismic design in structures in the Mississippi Valley region, a New Madrid quake could be expected to cause much more extensive and widespread damage than resulted from an event of similar magnitude in California. However, since expected effects of the moderate sized event are encompassed within the effects of the events examined here, a separate scenario for the moderate event is not presented.

To estimate the effects of earthquakes (magnitudes 7.6 and 8.6) in the New Madrid Seismic Zone on the six cities, the following procedures were employed. Structural inventory and critical facilities data were collected and supplemented in some cases by further investigations. Estimated levels of ground shaking in the six cities are expressed in Modified Mercalli Intensities and were provided by the U.S. Geological Survey for both the Ms=7.6 and Ms=8.6 earthquakes. These estimates depict ground shaking intensities which would be expected if each earthquake's epicenter were as close as possible, along the fault zone, to each studied city. On the Modified Mercalli Intensity scale, these estimates ranged between V and X. To assess expected structural damage, a series of fragility curves, (which describe the probability of damage states as a function of the level of ground shaking), were developed for sixteen different types of structures common to the six cities. These structural types included buildings, utility plants and systems, dams, bridges and storage tanks. The fragility curves were applied to the inventoried structures, usually grouped according to a function, to determine the expected damages at the ground shaking intensities estimated for the structure's location. Casualty estimates were based on the expected number of occupants of the buildings and the level of damage estimated to occur to them. Average building occupancies were derived from census data, employment data and inventory data. Restoration and replacement costs were estimated for those structures and systems for which damage estimates were made and were based on average construction costs in the cities studied, and the damage sustained. These determinations of damage, casualties and costs are preliminary estimates derived from implementation of a preliminary vulnerability assessment methodology and should be utilized accordingly.

If exposed to an occurrence of either of the postulated earthquakes, the six project cities would suffer varying effects. The following sections of this summary are a discussion of the overall effects and probable consequences for the six cities.

II - Casualties

The number of casualties (deaths and injuries) resulting from occurrence of either of the postulated events would depend on the time of day at which it occurred. At night, most of the population is found in relatively safe wood frame residential structures, but during a typical working day the majority of the population moves to buildings which are much more vulnerable to severe structural damage or collapse. A substantial proportion of the daytime casualties would occur among school children. Total daytime deaths in the six cities could easily exceed 4,500, as shown in the following summary:

Total Estimated Deaths
Due to Structural Failure

	Ms=7.6 Event			Ms=8.6 Event		
	Night	Day	School Deaths as % of Day Deaths	Night	Day	School Deaths as % of Day Deaths
Memphis	211	2523	26	435	3786	27
Paducah	47	116	18	101	201	19
Carbondale	29	74	30	69	160	25
Evansville	23	227	32	58	492	32
Poplar Bluff	1	17	88	4	52	81
Little Rock	3	64	16	9	216	17
Total	314	3021	26(avg.)	676	4907	27(avg.)

III - Medical Services

Medical services in the six cities would be severely burdened to provide adequate care for all injured persons requiring medical attention, except perhaps in Little Rock. Outside assistance may be a viable consideration for planners to alleviate this situation. Health care professionals would encounter difficulty reaching their places of work, and a few (less than two percent) would be among the dead and injured. The normal availability of beds and medical supplies would be reduced because of severely damaged or collapsed hospital structures. Memphis would be the most severely affected as seen in the following table.

City	Hospital Structures Surveyed	Hospital Beds Estimated to be Available: Ms=7.6 Event Number	Ms=7.6 Event % of Total	Ms=8.6 Event Number	Ms=8.6 Event % of Total
Memphis	25	3230	52	2290	37
Paducah	7	720	89	600	74
Evansville	20	2020	90	1620	72
Poplar Bluff	7	690	90	590	77
Carbondale	6	190	95	160	79
Little Rock	13	3760	100	3720	99
Total	78	10,610	86 (Avg)	8980	73 (Avg)

Most of the cities would not have sufficient surviving beds to accommodate the number of major injuries estimated in this report in addition to their normal load of patients. Other services would be similarly affected. The number of seriously injured persons requiring prompt medical attention would be about four times the number of deaths in each city. Additional casualties could also result from fires and flooding.

IV - Transportation Systems

Damage to transportation systems would seriously hamper rescue and relief efforts and would have an extensive adverse effect upon regional and national commerce.

Highway access to Memphis as well as major highway availability within the city would be severely limited for both seismic events. With the Ms=7.6 event, the most probable surviving access route would be U.S. 72 from the east; bridge collapses would either cut or block most, but probably not all, of the eight other principal arteries into the city. Poplar Bluff would be vulnerable to loss of highway access from the east. Paducah's highways would suffer some damage, but no serious loss of accessibility would result. Little loss of highway accessibility would occur in Carbondale and Evansville, and almost no serious highway damage would take place in Little Rock.

Damage to railway networks would follow a pattern similar to the highway damages. Little Rock would probably suffer no loss in rail accessibility; Evansville would experience little or none. Carbondale could suffer impaired accessibility from the west, while Paducah is most vulnerable to rail losses to the north (crossing the Ohio River) and from the east. The cities likely to suffer greatest disruption are Poplar Bluff and Memphis. Rail access from all directions into Poplar Bluff would be at risk of serious impairment, though not to the extent expected in Memphis, where over 75% of all system sections have relatively low survival probabilities.

These assessments are based on the likelihood of collapse of highway and railway structures. Some of the rail and highway structures which did not collapse would suffer severe damage that would restrict or prevent their use by heavy vehicles.

For both earthquakes, railway traffic would be stopped for as long as required to inspect all structures in each line segment, possibily 24 to 48 hours. For that reason, the most immediate transportation needs into and out of the six cities would have to be met via highway and air transport, and possibly by river access, although port facilities are likely to be seriously damaged.

River ports are expected to be extensively disrupted, with the minimum disruption occurring in Little Rock. The cities of Carbondale and Poplar Bluff do not possess river port facilities and thus would not be directly affected. Memphis, Evansville and Paducah are expected to sustain substantial damage to their river ports facilities.

Partial or limited availability of major airport facilities is expected following either earthquake. Those facilities at airports which rely on electrical power, e.g., navigation aids and runway lighting, may be out of commission for a period of time, even if emergency power is available. Runways may be available, at least for limited use, even in cities closest to the fault zone. Runways may sustain certain kinds of damage but still have enough useable length to allow landings and takeoffs of aircraft bearing vital supplies. The loss of navigation and landing aids can be significant, especially during winter when weather conditions are frequently marginal or below landing minimums.

V - Utility Systems

The six cities studied, for both earthquake events, are expected to experience serious impairment or loss of their four main utility systems (electric, water, gas, and sewers). Little Rock will lose availability of all systems in an Ms=8.6 event but may not lose availability of all systems for the Ms=7.6 event. Those which are out-of-service after the Ms=7.6 event are likely to be restored relatively quickly. Systems in the other five cities, for both events, will be unavailable for periods of days to months due to likely shortages of supplies, equipment and workers to restore the systems. The most essential and, unfortunately, the most vulnerable of the utility networks, are the electric power systems. So many things depend upon the availability of electric power that even its short term loss, under normal conditions, is a major setback to a community. To superimpose a loss of electric power upon a severe and widespread disaster can mean, for example, no water to fight fires or for drinking and sanitation; no light or heat; no communications; and no sewage pumps. The following summary presents the estimated availability of utility systems for the six project cities for the Ms=7.6 event. All systems are expected to be unavailable for the Ms=8.6 event.

City	Estimated Availability of Utility Systems Ms=7.6 Event			
	Electric	Water	Gas	Sewer
Memphis	U	U	U	M *
Little Rock	U *	A	M *	A
Evansville	U	U	U	U
Paducah	U	U	U	U
Carbondale	U	U	U	U
Poplar Bluff	U	U	U	U

U - System likely to be unavailable.
M - System may be available.
A - System likely to be available.
* - Limited and/or modified use possible.

VI - Critical Facilities

In addition to the examination of critical lifeline systems (utilities, hospitals, communications and transportation), the six cities' vulnerability to earthquakes includes an assessment of facilities that will be crucial to each community's ability to conduct and monitor its immediate response to the estimated losses, particularly those involving life protection. These facilities include police and fire stations, ambulance services, blood banks and clinical laboratories. In general, Little Rock and Evansville were found to be the relatively least vulnerable to damages to these structures while Memphis, Poplar Bluff and Paducah are the most vulnerable.

VII - Flooding

Were the earthquake to occur at a time when high water conditions (i.e. 100 year flood) existed in the area's rivers and streams, flooding of low-lying areas, now protected by levees, is likely to occur. This is because levees are expected to be damaged sufficiently to allow flooding behind them. Earthen dams, however, are not expected to be damaged to the extent that they will lose their reservoirs. This finding, combined with the situation that low or flood-prone areas in the six cities are mostly undeveloped and unoccupied, indicates that relatively few casualties would be expected due to flooding following the postulated seismic events. Flooding would, however, result in displaced persons and would hamper relief efforts.

VII - Fires

Giant fires, or conflagrations, involving major portions of the six cities are unlikely as a direct result of the scenario earthquakes, due to the nature and density of construction. Widespread individual or small-group structural fires are likely, however, due to miscellaneous damage-related factors, (i.e. gas leaks, flammable liquid spills, electric shorts, etc.), and loss of fire suppression capabilities.

VIII - Shelter Requirements

Many individuals will require shelter when their dwellings are rendered uninhabitable by actual earthquake-caused damage, flooding and other causes. These persons may have available alternative shelter in surviving, relatively undamaged structures (following inspections). The following is a listing of the estimated numbers of persons requiring shelter in the six cities:

Persons Likely to Require Shelter
Due to Damage to Residence

City	Due to Flooding	Ms=7.6 Event	Ms=8.6 Event
Memphis	10,100	231,680	353,800
Little Rock	3,500	2,440	21,700
Evansville	24,600	11,095	38,900
Paducah	5,000	13,318	22,600
Carbondale	-	5,728	11,100
Poplar Bluff	-	5,743	10,600
Total	43,200	270,004	458,700

Section IX - Restoration/Replacement Costs

The financial and economic burden placed upon the region and the entire nation by an occurrence of such a disaster would be very great. The following summarizes a part of such costs (restoration and replacement) for the six cities.

Estimated Restoration/Replacement Costs
(Millions of Dollars)

City	Ms=7.6 Event Structures	Utilities	Total	Ms=8.6 Event Structures	Utilities	Total
Memphis	$22,095	2,908	25,003	27,609	4,071	31,680
Little Rock	1,463	454	1,917	2,886	955	3,841
Evansville	4,781	360	5,141	7,395	595	7,990
Paducah	3,002	1,395	4,397	3,846	1,952	5,798
Carbondale	809	257	1,066	1,185	387	1,572
Poplar Bluff	558	135	693	858	217	1,075
Total (Millons of Dollars)			$38,217			$51,956

X - Summary

In summary, the impact of either the Ms=7.6 or Ms=8.6 earthquake on the six cities would be massive and could cause widespread disruption, damage, and casualties. Remaining resources within the affected region would be unable to adequately provide for the emergency response needs of these communities. This indicates that very large scale outside support and assistance of all kinds may be the primary means to reduce further loss of life, suffering and disruption to regional lifelines. It is hoped that the information contained within this report will be a meaningful step toward the development of appropriate national, regional and local response plans, and longer range strategies.

XI - Organization of this Report

The material contained in this report can be divided into two major areas. The first, Sections 1 and 2, describes the overall project and its methodology. The second, Section 3, is a presentation of the project's findings and consists of an initial general section which contains discussions of each results category, and which also presents findings and conclusions pertaining to all or most project cities collectively. Then follow the six sub-sections presenting and discussing the findings for each project city. An estimation of replacement and restoration costs, glossary, abbreviations list and a bibliography conclude the report.

THE DECEMBER 7, 1988, SPITAK (SSR) EARTHQUAKE

By
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INTRODUCTION

On December 7, 1988, when the magnitude 6.8 earthquake struck Soviet Armenia at 11:41 a.m. local time, leaving an estimated 25,000 dead, 18,000 injured, 510,000 homeless, and reconstruction costs of $16 billion, the world was reminded of what a damaging earthquake can do to a nation, its urban centers, gross national product, and the societal fabric. An earthquake:

- o shows whether preparedness planning and mititgation measures were adequate, or not,

- o tests the siting, design, and construction practices for lifelines, buildings, and critical facilities, and

- o stretches the capacity of the populance to respond to the disaster and to make appropriate modifications in practices during the long recovery period.

IMPORTANT LESSONS

Multidisciplinary studies of the Soviet Armenia earthquake by a U.S. team of experts and previous studies of other earthquakes have taught us many important lessons. Several are singled out in the context of Armenia:

- o A community that does nothing to prepare for a damaging earthquake sows the seed of disaster, especially if damaging earthquakes have occurred in the past.

  Armenia was unprepared for such an earthquake, even though damaging earthquakes have occurred there in the past.

- o The destructiveness of an earthquake depends on its size, proximity to urban centers, and the state-of-preparedness in the urban centers. Armenia was unprepared, the earthquake was the largest in their history, and villages like Spitak took a "direct hit" in the epicentral region.

- o The time factor is extremely important. The critical time frames are:

  -- <u>seconds</u> for duration of ground shaking,
  -- <u>minutes</u> for the first occurrence of the aftershock sequence and the build up of pore water pressue in liquefiable soils,

-- <u>hours to a few days</u> for emergency response and search and rescue activities,
-- <u>days to years</u> for predictions and warning and personal preparedness,
-- <u>years to decades</u> for community preparedness and recovery programs, and
-- <u>decades to centuries</u> for the seismic cycles of various active faults to be completed.

Armenia could have been spared much of the devastation <u>if</u>: a) the earthquake had occurred 5 minutes later when the school children were outside the schools that were destroyed and on their way home for lunch, b) the level of personal preparedness had been greater, and c) the level of community preparedness had been greater.

o Earthquake prediction and warning are of limited value when the societal component is not as well developed as the scientific component.

Soviet authorities had been advised three years ago by scientists of the increased probability of a damaging earthquake in Armenia, but no action was taken.

o A primary cause of damage to buildings is underestimation of the amplitude, frequency composition, and duration of the ground shaking. The earthquake had an epcientral intensity of MSK IX-X; whereas, the design was for intensity VII, i.e., about one-eighth the actual force level.

o Good quality of construction provides a margin of safty to compensate for uncertainties scientists and engineers face in siting and design. Quality of construction and detailing were poor in Armenia. Modern buildings designed and constructed in the 1970's failed and became death traps primarily because the floor systems were not constructed and anchored in a way that allowed them to participate with the strucutre in the absorption of energy.

o Almost all earthquakes produce "surprises" because we either have not learned everything we need to know about the nature and effects of earthquakes, or we have not done a good job of applying what we do know. A damaging earthquake exposes the flaws in:

-- siting and design of structures and lifeline systems,
-- construction practices,
-- emergency response, and
-- personal and community preparedness.

Armenia experienced the following "surprises:" a) the harsh realities of the first 24 hours of search and rescue in a winter environment, b) the vulnerability of precast reinforced concrete frame buildings--for which a large inventory still exists in Yerevan (the capital) and in other parts of the Soviet Union, and c) the injury to death ratio, which is typically 3 or 4 to 1, was reversed in the earthquake-creating a major public health problem.

SUMMARY

The Spitak earthquake provided many important lessons that can be adapted to every earthquake-prone part of the United States. On May 23-27, 1989, representatives of the U.S. team that went to Armenia after the December 7 earthquake and other specialists met in Yerevan to share their insights with representatives of the French and Japanese teams. These insights were offered to Soviet authorities as recommendations to aid the Soviet's reconstruction program and as proposals for cooperative endeavors should reduce the chances of a disaster like this one from happening again in the Soviet Union and other parts of the world.

TECHNICAL INFORMATION FROM THE U.S. TEAM'S FIELD INVESTIGATIONS OF THE DECEMBER 7, 1988, ARMENIA EARTHQUAKE

The magnitude 6.8 Spitak earthquake which struck Soviet Armenia at 11:41 a.m. local time on Wednesday, December 7, 1988, caused the following impacts:

- twenty thousand injured,
- an estimated 60,000 dead, (the exact number may never be known),
- five hundred ten thousand homeless,
- collapse and heavy damage to buildings (including hospitals, schools, apartment buildings and industrial facilities):
  - in Spitak: damage to 100% of the building stock, with at least 12,000 to 15,000 dead,
  - in Leninakan: damage to 80% of the building stock, with at least 10,000 to 12,000 dead, and
  - in Kirovakan: damage to 50% of the building stock, with at least 450 dead.
- extensive social disruption, and
- reconstruction costs that are estimated to reach $16 billion or more.

These impacts made this earthquake one of the worst natural disasters of the twentieth century. The Spitak earthquake was a disaster of modern precast-concrete-frame-panel buildings constructed in the 1970's and 1980's. In the Soviet Union, building construction is typically planned in Moscow where a limited number of basic general building designs are prepared for implementation repeatedly throughout the nation. Initially, the designs do <u>not</u> incorporate seismic loads and a local agency modifies the general design for seismic loads when they are applied in a region characterized by moderate-to-high seismicity. Both a building code prescription and a microzonation strategy are used.

In Armenia, the principal building types were:

- <u>stone-bearing wall buildings</u>, the traditional construction technique until 1970. These buildings were limited in height to five stories. The masonry walls are thick, lack steel reinforcement, and provide both lateral and vertical support for the hollow core concrete plank floors and roofs which were introduced in the 1950's and 1960's.

- o <u>composite frame and stone wall buildings</u>, mostly 4- and 5-story buildings consisting of exterior stone shear walls and a framing system cast within the walls as well as the interior of the building.

- o <u>precast concrete frame-panel buildings</u>, which began in the 1970's and today are the predominant design for residential and industrial structures. In the affected area, the tallest of these buildings was nine stories with one-story penthouses. Floors and roofs are precast hollow-core concrete planks that bear on the walls but have no connections. The buildings have steel reinforcement.

- o <u>precast concrete-panel buildings</u>, a contemporary building type in Armenia which was just beginning to be widely constructed for public and residential use. They ranged in height to nine stories. Floors and roofs are also precast hollow-core concrete planks. They are relatively stiff.

- o <u>concrete lift-slab buildings</u>, which involve either one central core or double cores of cast-in-place concrete shear walls. Elevated floor and roof slabs are cast at grade, lifted into place, and supported by columns. The cores provide lateral stability for the structure. Building performance depends strongly on the quality of the attachments of the slabs to the cores. Only two buildings of this type--one of 10 stories and another of 16 stories--had been erected in Leninakan at the time of the Spitak earthquake. Both buildings were heavily damaged, requiring subsequent demolition.

In the 400 square kilometer epicentral region affected most severely by the Spitak earthquake, the damage statistics for the four principal types of buildings (see Table 1) stone bearing wall, composite frame and stone wall, precast concrete frame-panel, and precast concrete-panel) are:

-- 314 buildings collapsed,
-- 641 needed to be demolished,
-- 1,264 needed repairs or strengthening, and
-- Only 712 (24%) remained habitable after the earthquake.

The Spitak earthquake produced two contrasts in performance:

-- the performance of precast concrete frame-panel buildings in Leninakan versus their performance in Kirovakan, and

-- the performance of precast concrete frame-panel versus the performance of precast concrete-panel buildings.

In Leninakan, 54% of the precast concrete frame-panel buildings collapsed, 41% will have to be demolished, 5% will need repairs, and none escaped damage. In contrast, in Kirovakan, none of the precast concrete frame-panel buildings collapsed or needed to be demolished and 19% escaped damage altogether. The explanation--site amplification in the 1.0 to 2.5 second period band by the deep (200-300 m; 660-1000 ft) lake bed deposits underlying Leninakan; soils in Kirovakan are thinner and stiffer. Also, the buildings in Kirovakan are limited in height to 5 stories.

The damage distribution is given in table 1 above. Armenian engineers rated the epicentral intensity as IX to X (MSK scale). They estimated that levels of horizontal peak ground acceleration may have reached 0.50 to 1.0g in Spitak, possibly with a large vertical component as well because of the thrust fault. The estimated level in Leninakan was about 0.40g, based on seismoscope records.

Recorded peak ground acceleration values are 0.21 g at Ghoukasian, located 27 km north of Leninakan, and 0.06 g at Yerevan, located 100 km from the epicenter.

In Armenia, most designs were for an intensity (MSK scale) of VII to VIII, with reductions being permitted for volcanic tuff foundation materials.

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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

$$T_s = \frac{4H}{V_s} \tag{1}$$

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 <u>approximately</u> by the relation

$$T_b = \frac{N}{10} \tag{2}$$

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.

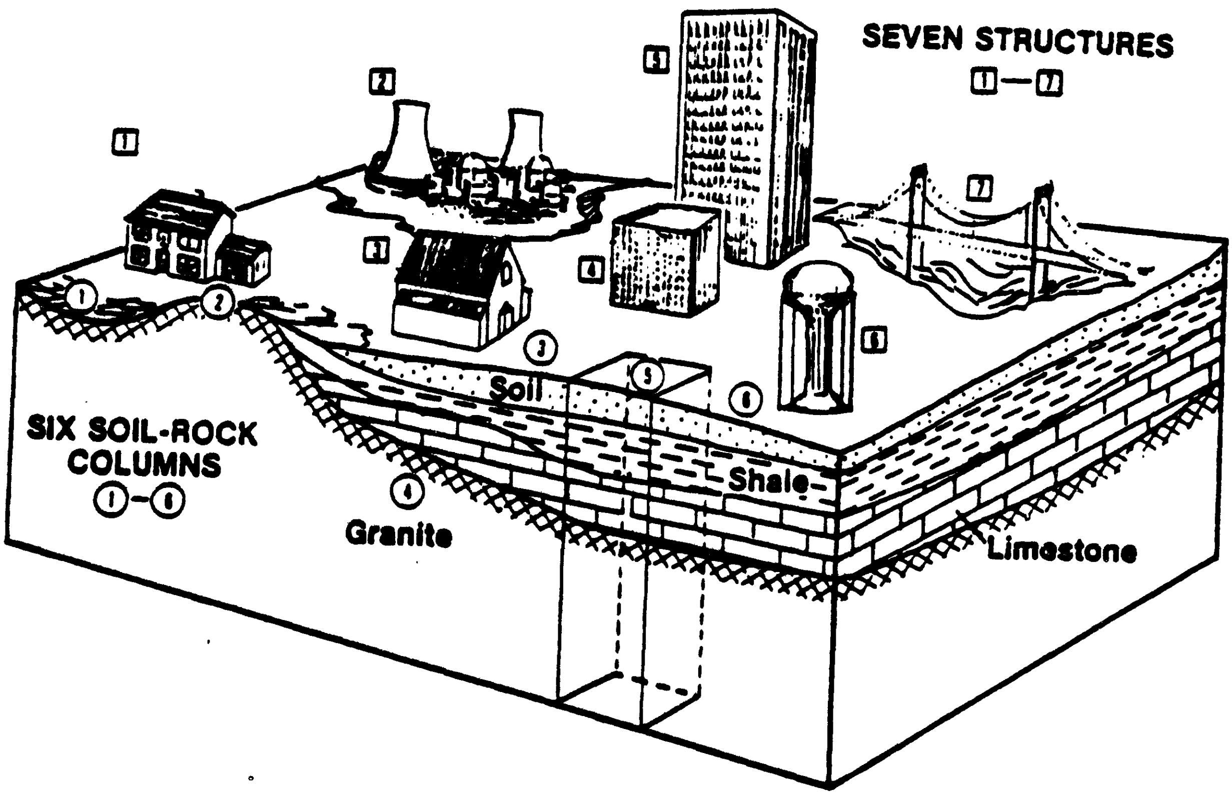

Figure 1.--Schematic illustration of six soil-rock columns and seven types of structures. Each soil-rock column and each structure have a fundamental nature period of vibration. If the dominant period of the earthquake-induced ground response coincides with the dominant period of the structural response,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

Site Physical Parameters and Their Effects on Ground Motion

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

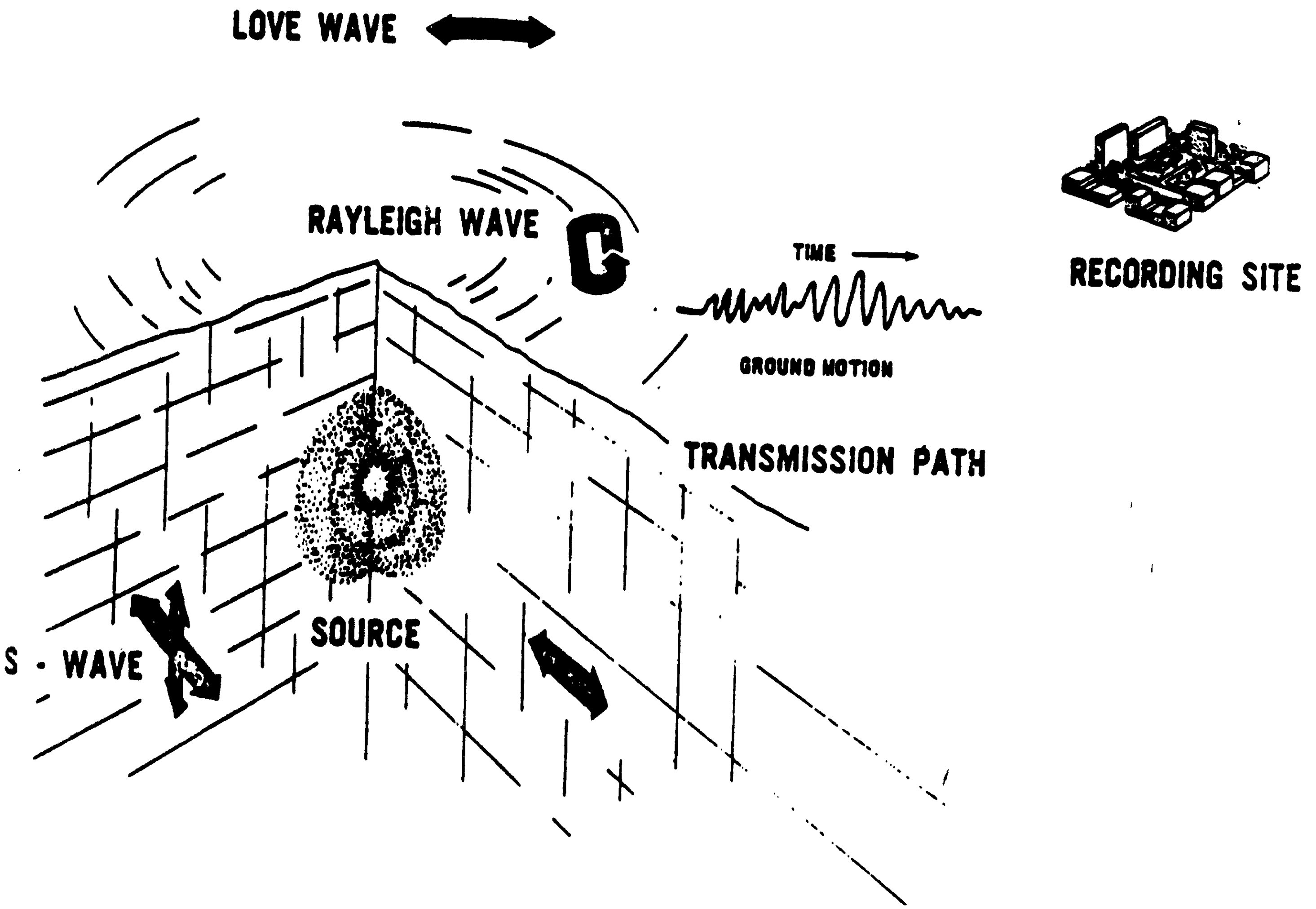

Figure 2.--Schematic illustration of the elements that contribute to the amplitude and frequency composition of earthquake ground motion recorded at a site. The local geology underlying the recording site acts like a filter and can significantly amplify certain frequencies of the ground motion input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

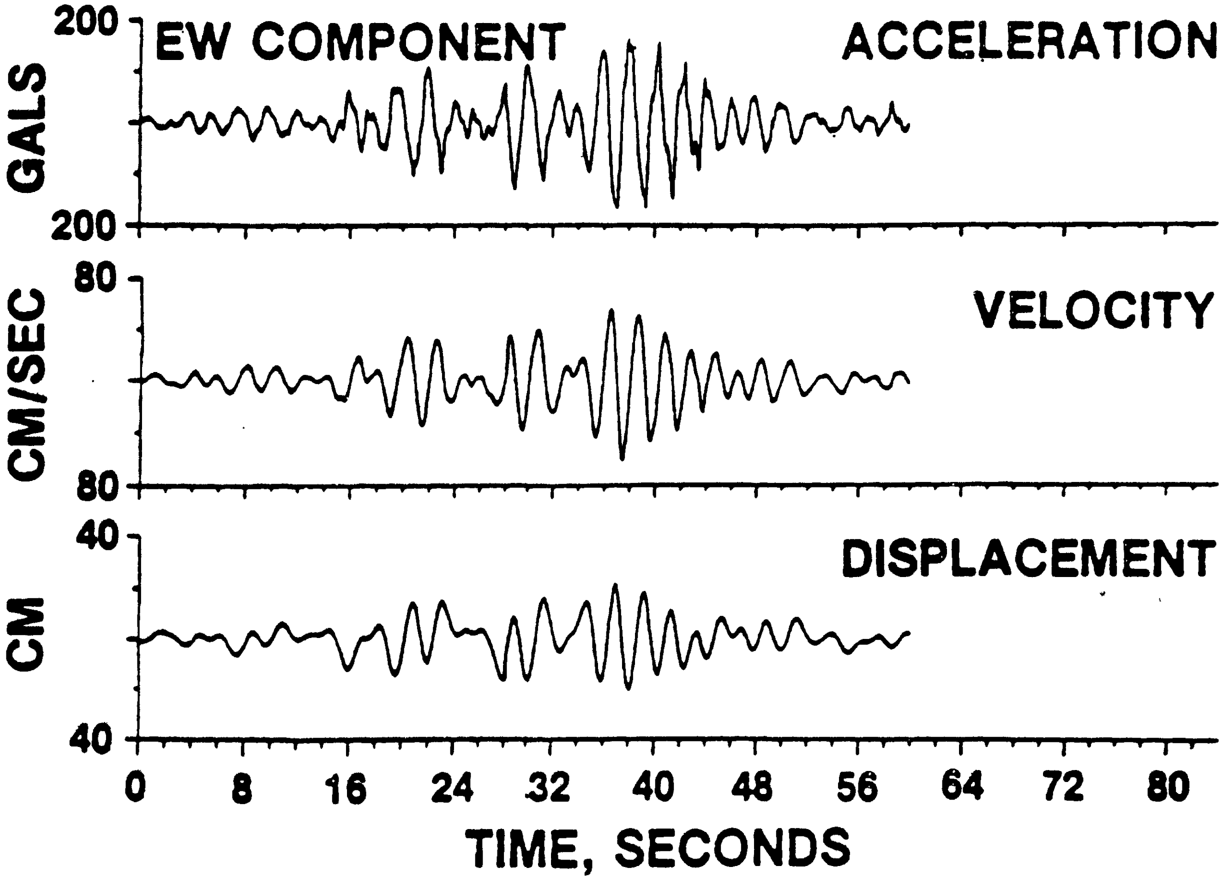

Figure 3.--Accelerogram (top) recorded at a free field location on the surface of the 50-meter thick lake beds forming the foundation in parts of Mexico City. The epicenter of the September 19, 1985, Mexico earthquake was located some 400 km to the west. The strong 2 second period energy in the accelerogram 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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EXERCISES TO ILLUSTRATE SOME OF THE TECHNICAL JUDGMENTS MADE IN EARTHQUAKE HAZARD AND RISK ASSESSMENTS

1. Earthquake source, path, and site.

2. Earthquake threat.

3. Faults and Maximum Magnitude.

4. Isoseismal Maps.

5. Strong Ground Motion.

6. Ground Shaking and Structural Response.

7. Soil Amplification.

8. Risk.

9. "What If . . ."

10. Recognizing and Reducing Vulnerability.

11. Liquefaction.

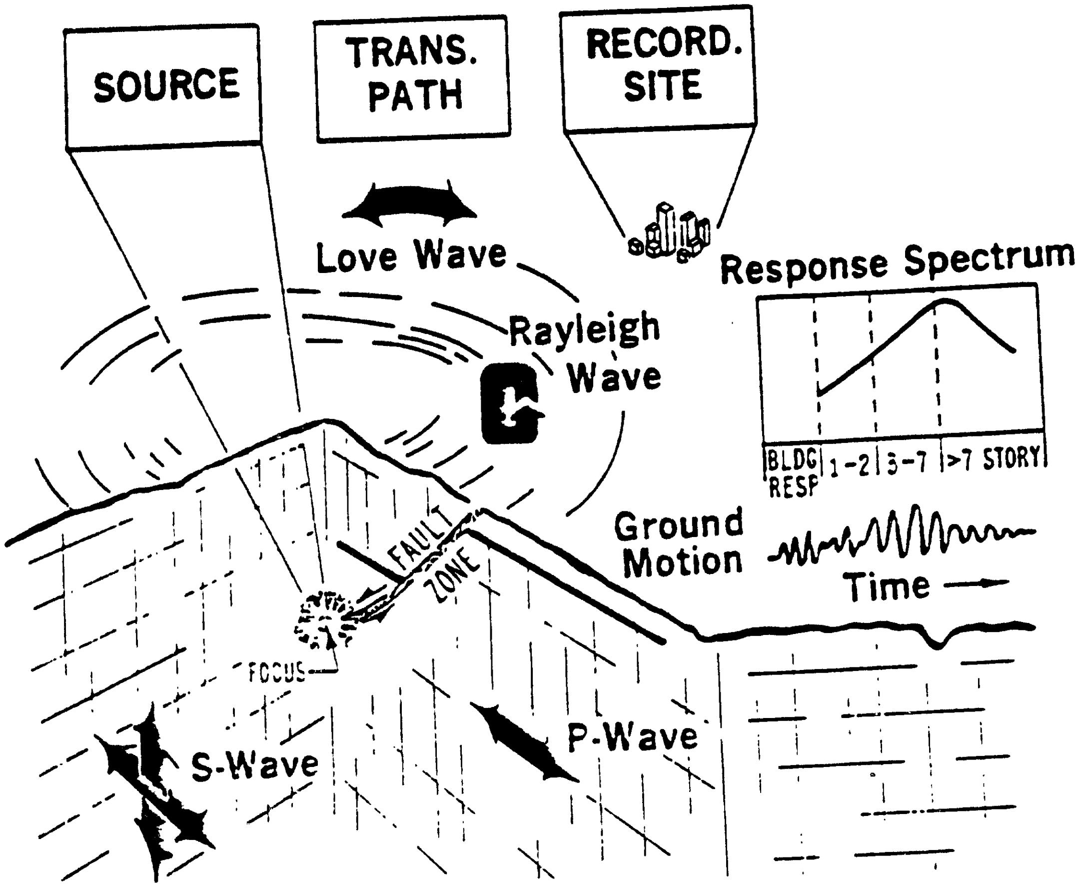
12. Building Code Zone Maps.

13. Living with Natural Hazards.

TECHNICAL JUDGMENTS ABOUT THE EARTHQUAKE SOURCE, PATH, AND SITE

The characteristics of ground motion occurring at a site in an earthquake are a function of the energy released at the source, the regional transmission path over which the seismic waves propagate, and the local soil and rock column underlying the site. Buildings at the site vibrate as a consequence of the frequency-dependent characteristics of ground motion induced by the geology of the source, path, and site.

Element	Key Variables
Source	Magnitude, Focal Depth
Trans. Path	Distance
Record. Site	Alluvial Thickness Impedance Mismatch



In order to design and build earthquake-resistant buildings, knowledge of the amplitude, spectral composition, and duration of the ground shaking is needed. This requires careful consideration of the physics of the source, transmission path, and recording site.

Question 1: Match each physical parameter below with the effect it has on the ground motion.

PHYSICAL PARAMETER		PHYSICAL EFFECT ON GROUND MOTION
SOURCE		
___ Fault Length	a.	Affects low frequencies; used to calibrate magnitude of great earthquakes.
___ Fault Activity	b.	Affects low frequencies mainly; used to scale acceleration in earthquake-resistant design.
___ Fault Rupture	c.	Affects high frequencies and peak acceleration.
___ Epicenter	d.	Affects partition of body and surface wave energy.
___ Hypocenter	e.	Affects location of design earthquake relative to site.
___ Stress Drop	f.	Affects focusing of energy at sites located at end of fault.
___ Magnitude	g.	Affects frequency of occurrence of earthquakes of various size.
___ Seismic Moment	h.	Affects magnitude of earthquake and duration of shaking.
REGIONAL TRANSMISSION PATH		
___ Distance from the Fault	i.	Affects high frequencies more than low frequencies because earth acts like a low-pass filter.
___ Q	j.	Correlates with rate of heat flow.
LOCAL RECORDING SITE		
___ Spatial change in thickness and shear wave velocity of soil/rock columns.	k.	Affects the amplitude, spectral composition, and duration of surface ground motion relative to that at a site underlain by rock or a uniform layer of soil.
___ Thickness of soil/rock column.	l.	Causes damping of soil to increase and effective shear wave velocity to decrease.
___ Shear wave velocity of soil.	m.	Affects the amplitude of the frequency-dependent site amplification.
___ Level of dynamic shear strain	n.	Affects the natural frequency of vibration of soil column.

TECHNICAL JUDGMENTS ABOUT THE EARTHQUAKE THREAT TO YOUR COMMUNITY

Question 2: Refer to the map of seismic source zones and the accompanying table to identify the two seismic source zones that are closest to your home. From the table, determine:

____ a) the maximum intensity, and

____ b) the maximum magnitude for earthquakes occurring in these two source zones.

____ c) Refer to the charts showing how peak horizontal ground acceleration attenuates as a function of magnitude to determine the approximate level of peak acceleration expected at your home.

Table: Maximum Magnitude and Intensity for seismogenic zones in the Mississippi Valley Region (Source: Algermissen and others, 1982).

1. Seismogenic Zones 69, 78-86, and 88-94 are assigned M max of 6.1.

   Seismogenic Zones 98 and 100 are assigned M max of 7.3.

   Seismogenic Zone 87 is assigned M max of 8.5.

2. For intensity, use the relation

   $M = 1 + 2/3\ I_o$

   or

   $I_o = 1.5\ (M-1)$

3. Zone 81 bounds the Ozark Dome and corresponds to the St. Louis arm of the Reelfoot Rift.

   Zone 82 corresponds with Ouachita Mountains.

   Zone 83 is the southwest extension of New Madrid Seismic Zone.

   Zones 80, 84, 90, and 94 follow the trends of the Nashville Dome, Central Missouri High, Mississippi River Arch-Wisconsin Arch, and Cincinnati Arch respectively.

   Zone 87 is the New Madrid Seismic Zone.

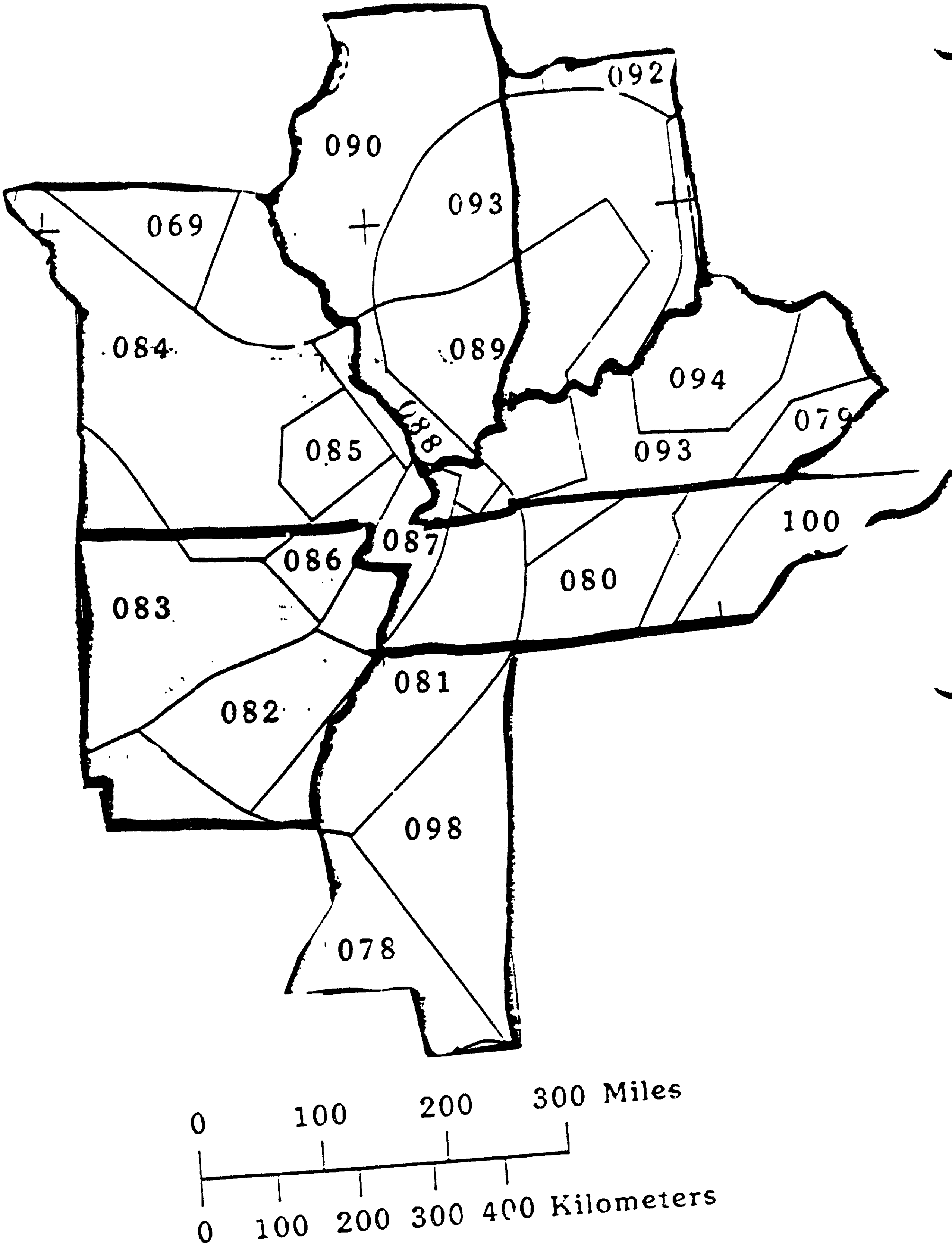
   Zones 92 and 95 correspond with the margins of the Wisconsin and Appalachian Basins.

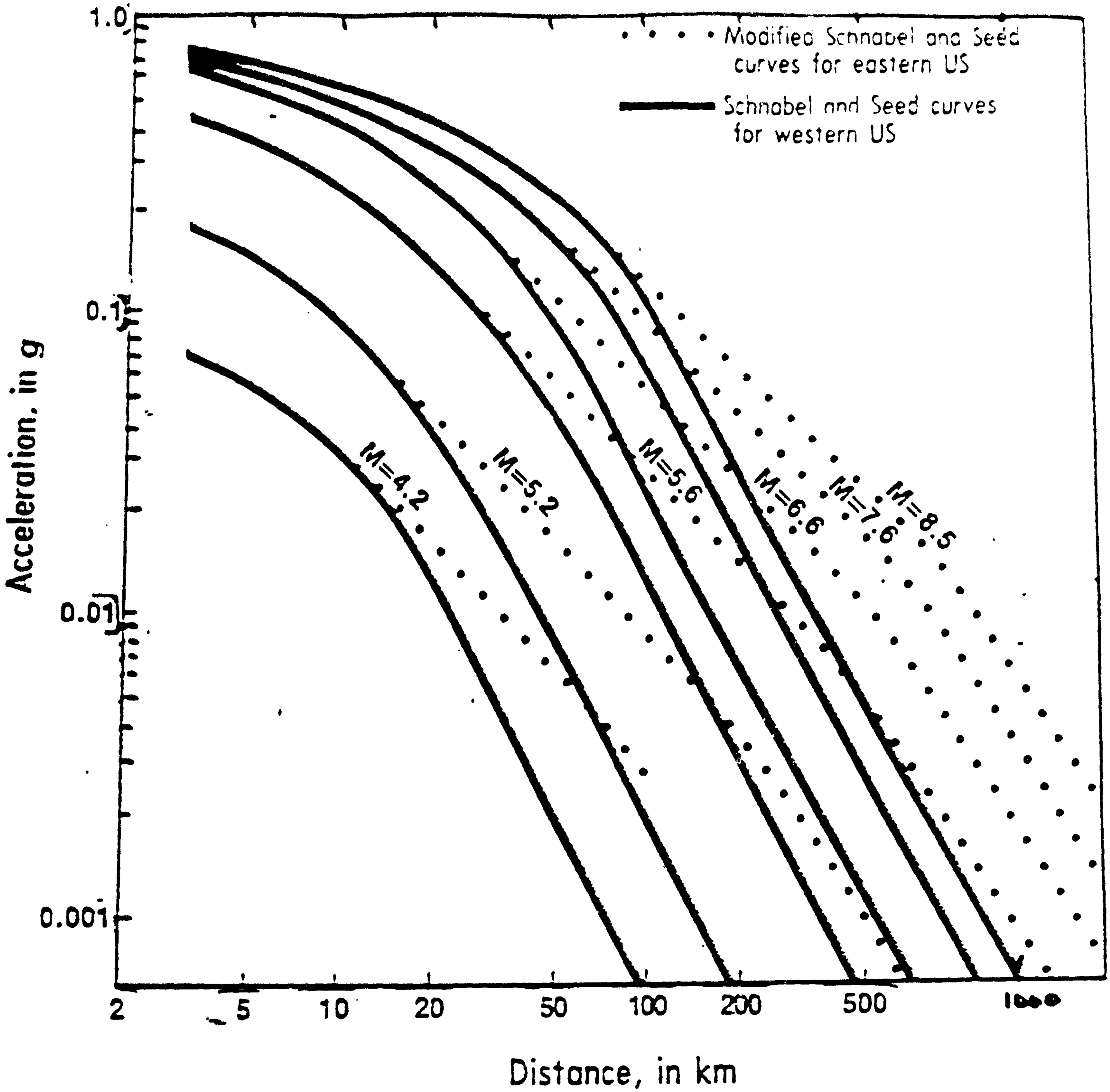
   Zone 89 corresponds with a large portion of the Illinois Basin, Wabash Valley Fault Zone, and a possible extension of the Reelfoot Lake Rift into Indiana.

   Zone 98 corresponds with the Gulf Coast.

   Zone 100 corresponds with the thrust faulted Appalachian trend.

SEISMOGENIC ZONES





Graph of regional seismic wave attenuation rates for Western (solid lines) and Eastern (solid plus dotted lines) United States.

TECHNICAL JUDGMENTS ABOUT FAULT RUPTURE LENGTH AND MAXIMUM MAGNITUDE

Question 3: Use the values of the total surface length of some well known fault systems in the world listed below and the chart to determine the maximum magnitude:

a) Jordan rift -- 1,000 km; M = ________

b) San Andreas Fault Zone -- 1,000 km; M = ________

c) Wasatch Fault Zone -- 370 km; M = ________

d) Queen Charlotte-Fairweather, Alaska -- 300km; M = ________

e) Garlock Fault Zone -- 240 km; M = ________

f) Greater Northern Puerto Rico (including the offshore segments) -- 179 km; M = ________

g) Calavaras -- 160 km; M = ________

h) Greater Northern Puerto Rico -- 60 km; M = ________

i) Oued Fodda (Algeria) -- 47 km; M = ________

j) Sierra Madre Fault Zone -- 16 km; M = ________

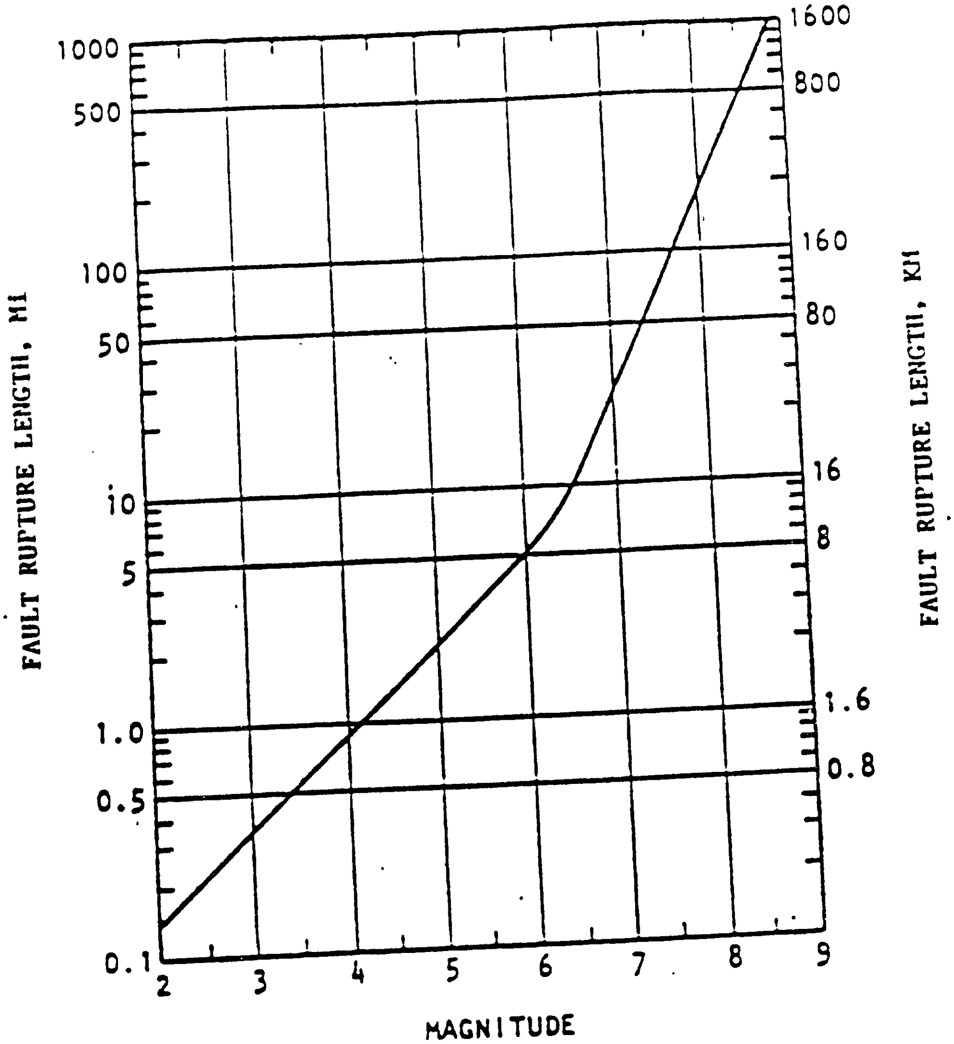
k) No Name (everywhere) -- 10 km; M = ________

l) New Madrid Seismic Zone (southern segment) -- 150 km; M = ________

m) New Madrid Seismic Zone (central segment) -- 75 km; M = ________

n) New Madrid Seismic Zone (northern segment) -- 100 km; M = ________

Assume that 50 percent of the total fault length ruptures.



Graph to use when estimating maximum magnitude from the fault rupture length.

TECHNICAL JUDGMENTS ABOUT ISOSEISMAL MAPS OF HISTORICAL EARTHQUAKES

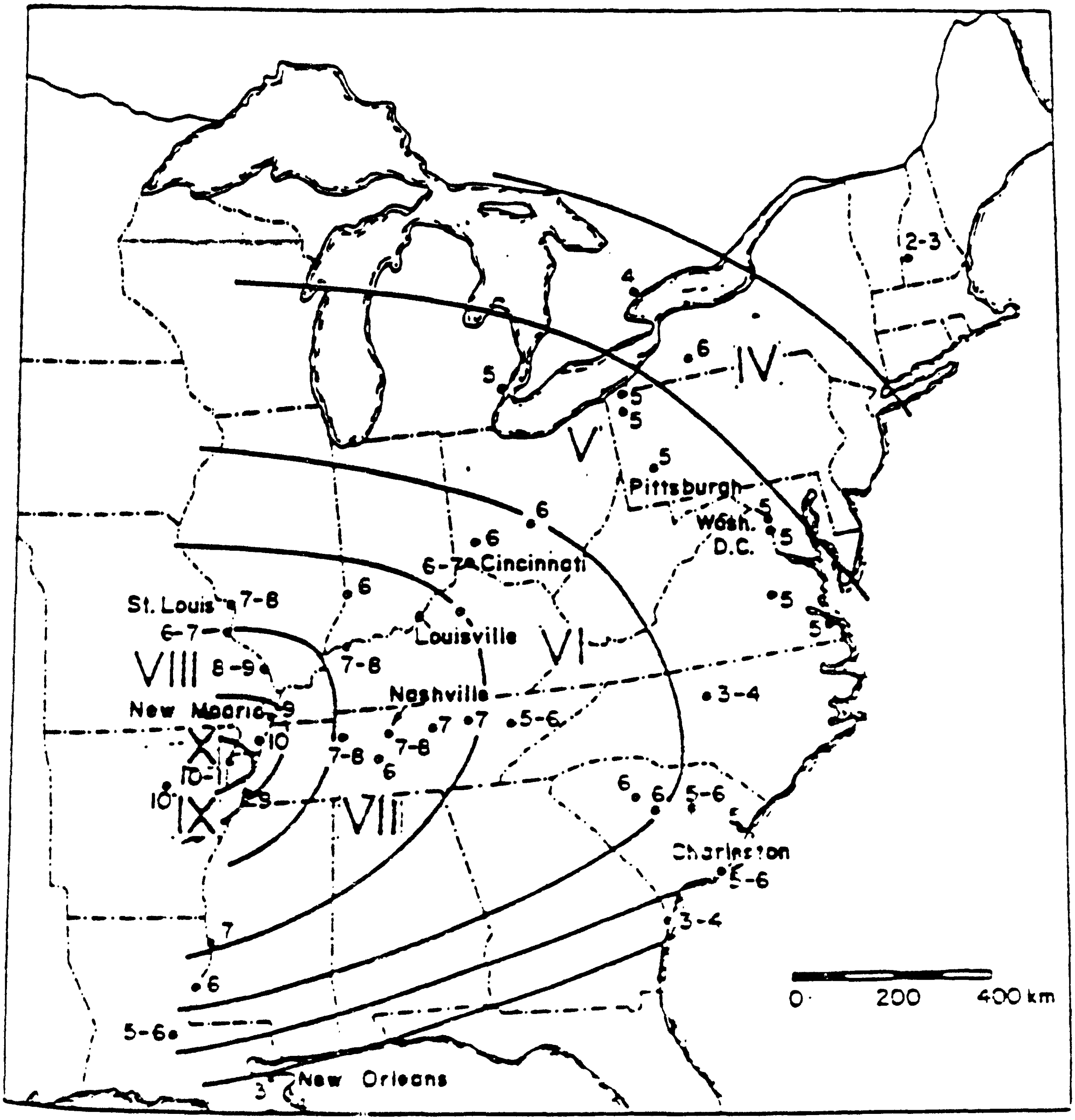
Question 4: Intensity Data and Peak Ground Motion

When strong motion instruments are unavailable to record the ground motion in an earthquake, values of Modified Mercalli intensity are assigned to denote the damage, such as for the 1811-1812 New Madrid earthquakes (see map below).

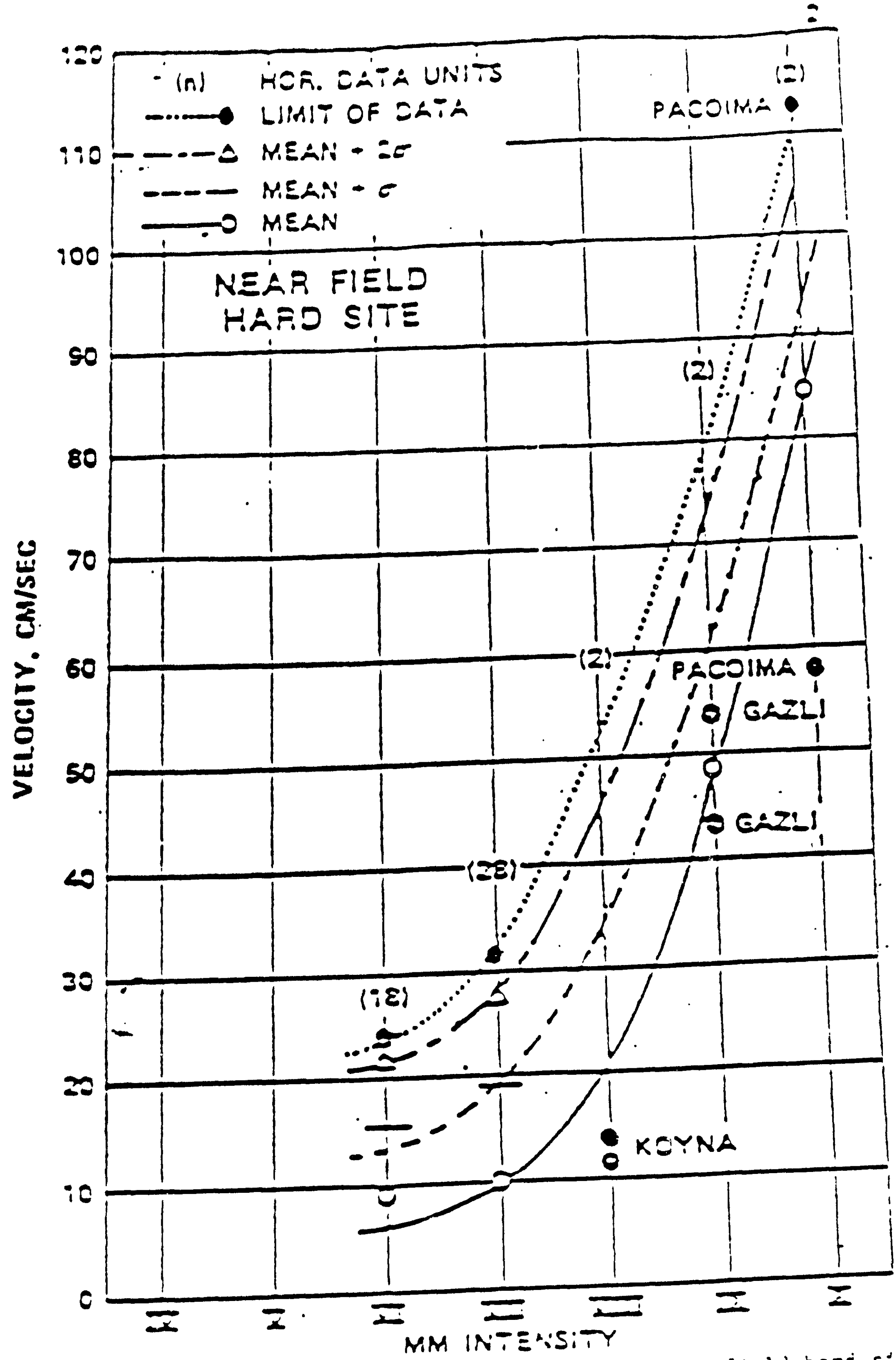
Use the curves on the following pages to estimate the actual peak ground acceleration and peak ground velocity at:

New Madrid ______________ St Louis ______________

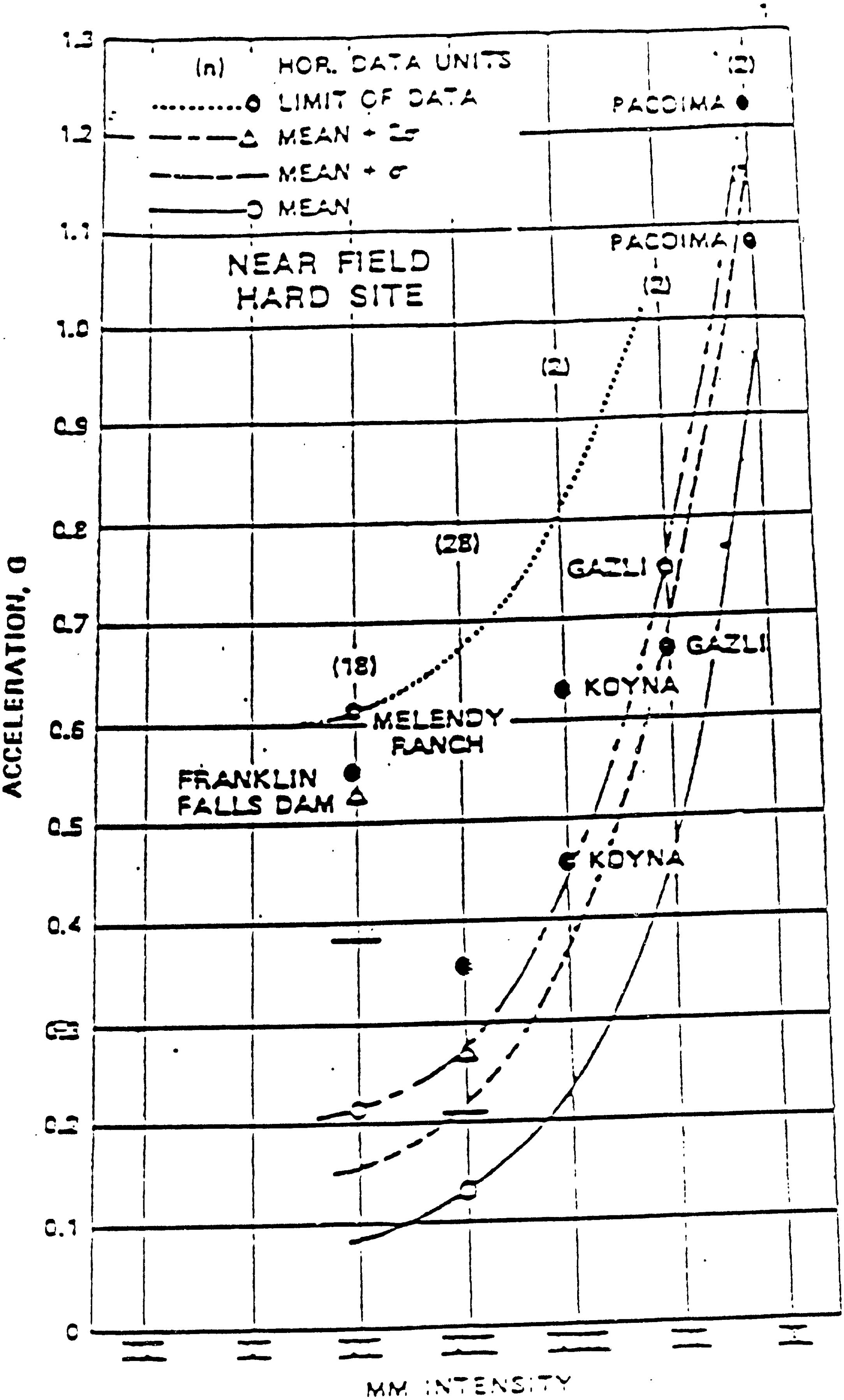
Memphis ______________ Washington ______________



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



Velocity as a function of MM intensity for a near-field hard site.



Acceleration as a function of MM intensity for a near-field hard site.

Question 5: Understanding Strong Ground Motion Records.

The following graphs illustrate:

1) two time histories,

2) their response spectra, and

3) their energy integrals.

I. Read the records and their derivative products to determine:

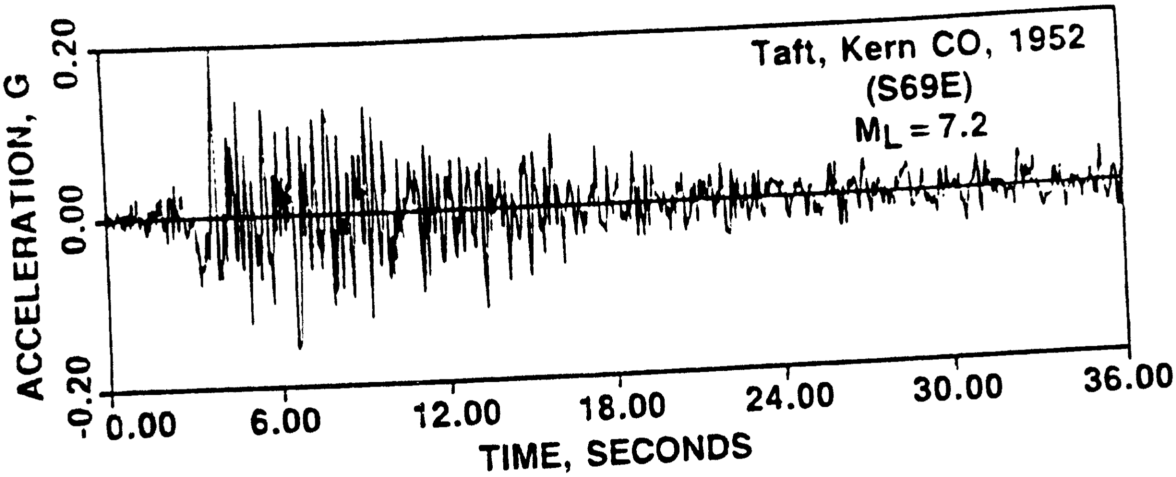
		Taft	Melendy Ranch
a.	Peak acceleration	______	____________
b.	Period of dominant spectral component	______	____________
c.	Duration	______	____________

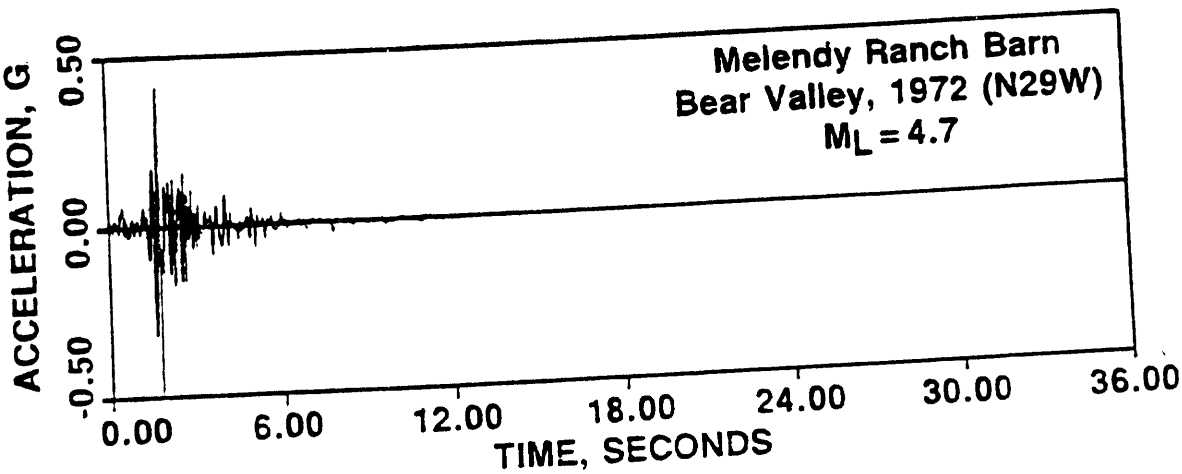
II. Which type of building would you like to be in if you experienced Taft? ____

III. What are the most significant parameters of ground shaking?

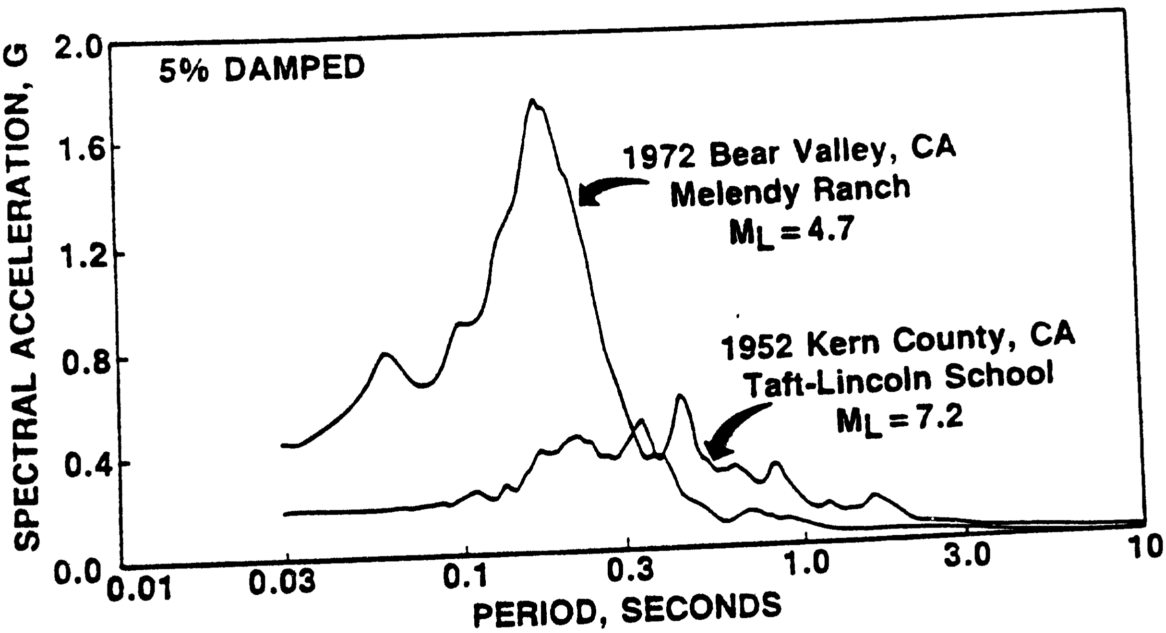
____

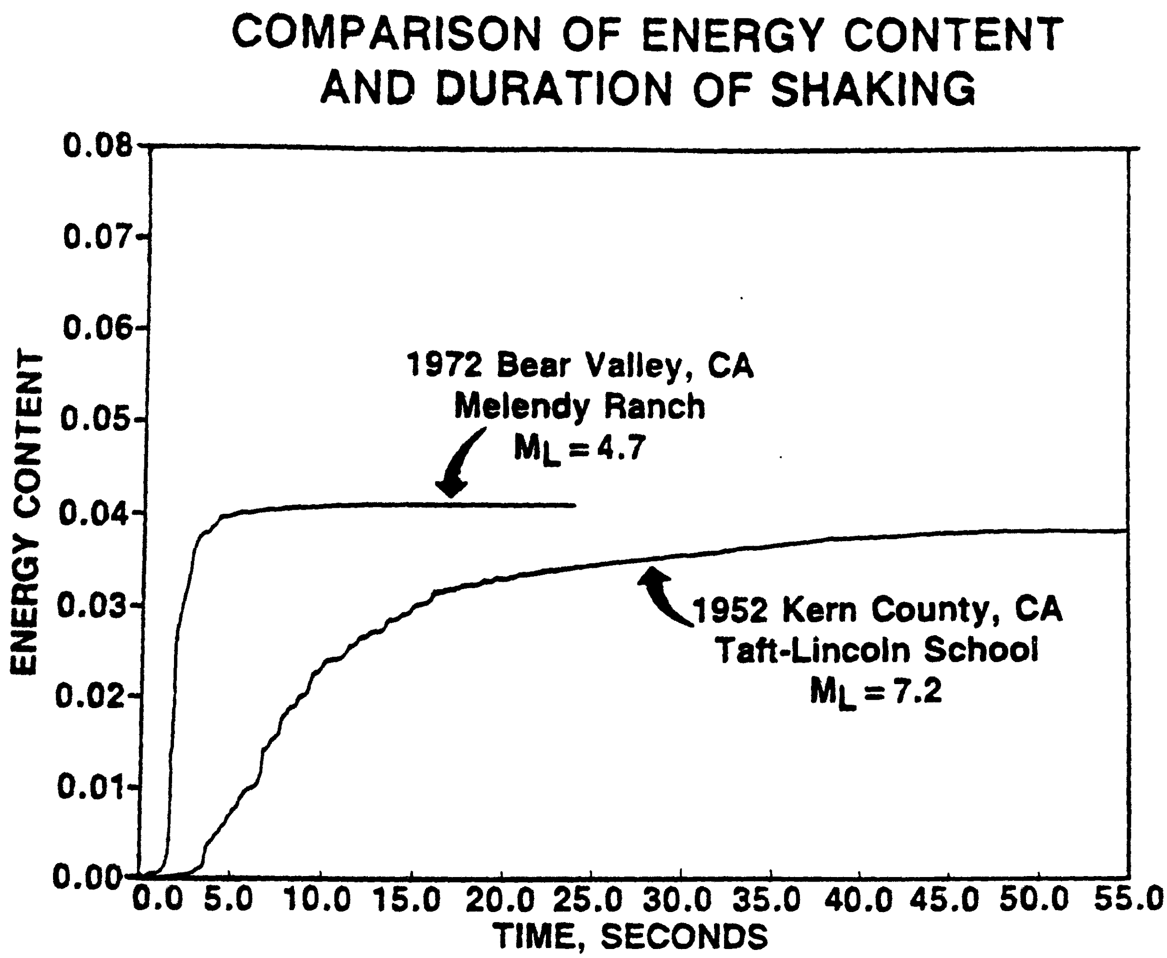
COMPARISON OF TIME HISTORIES





COMPARISON OF SPECTRA

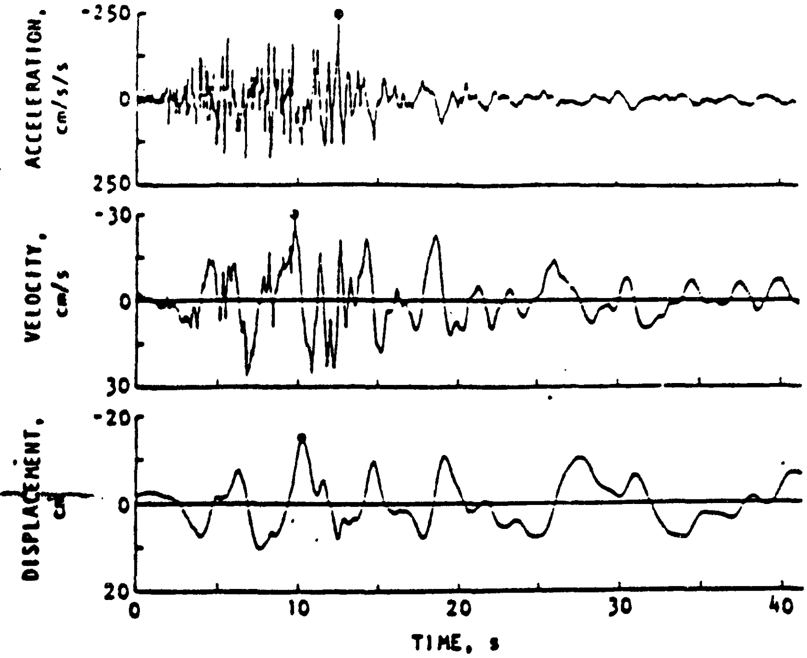




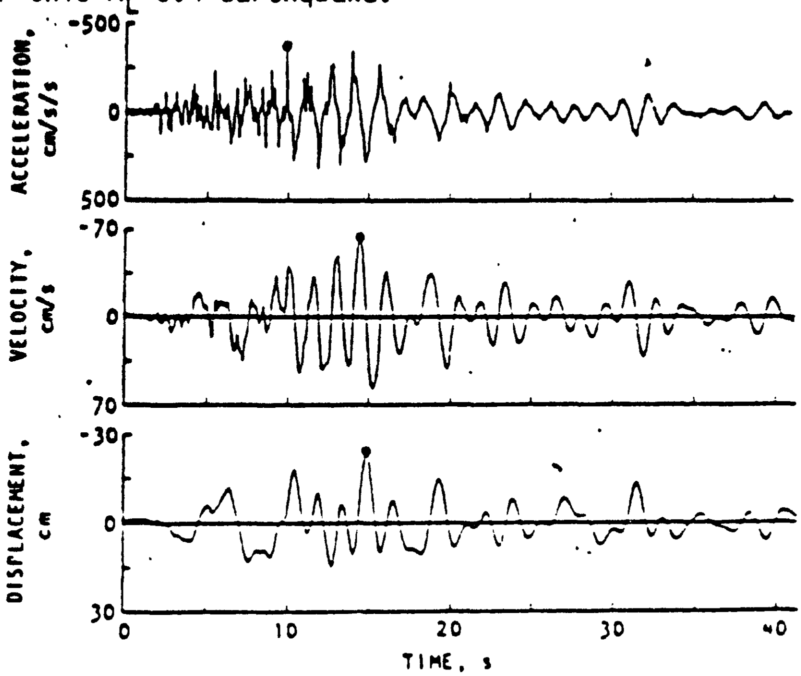
COMPARISON OF ENERGY CONTENT
AND DURATION OF SHAKING
ENERGY CONTENT
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
1972 Bear Valley, CA
Melendy Ranch
$M_L = 4.7$
1952 Kern County, CA
Taft-Lincoln School
$M_L = 7.2$
0.0 5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0 55.0
TIME, SECONDS

TECHNICAL JUDGMENTS ABOUT THE PHYSICAL CHARACTERISTICS OF GROUND SHAKING AND STRUCTURAL RESPONSE

Question 6: Referring to the following strong motion records, determine the peak values of horizontal ground acceleration, velocity, and displacement. Do the same for the roof motions. Why are the roof motions greater? Why is the frequency composition of the roof motions different from the ground motions?



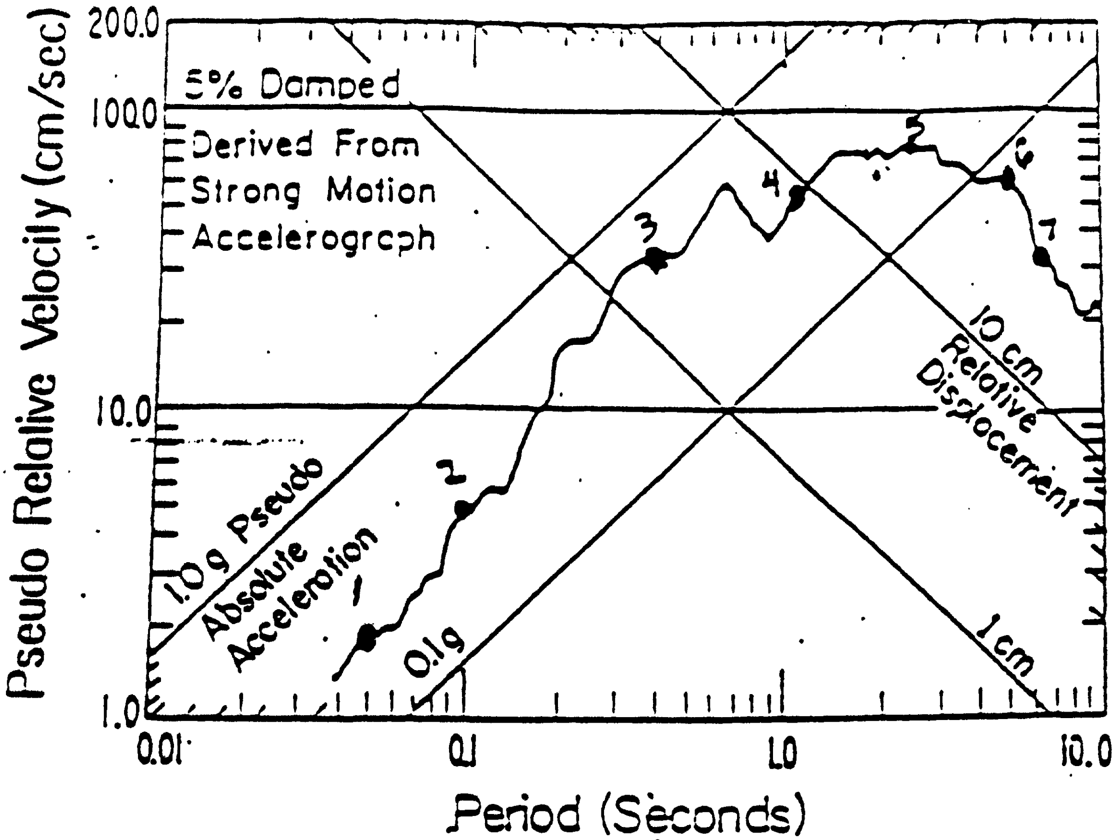
North-south ground motion at Holiday Inn during the San Fernando earthquake. The accelerograph was approximately five miles from the closest portion of the causative fault of this M_L 6.4 earthquake.



North-south roof motion of Holiday Inn during the San Fernando earthquake. This building is a 7-story reinforced concrete frame building. These recorded buildings motions enable an analysis to be made of the stresses and strains in the structure during the earthquake.

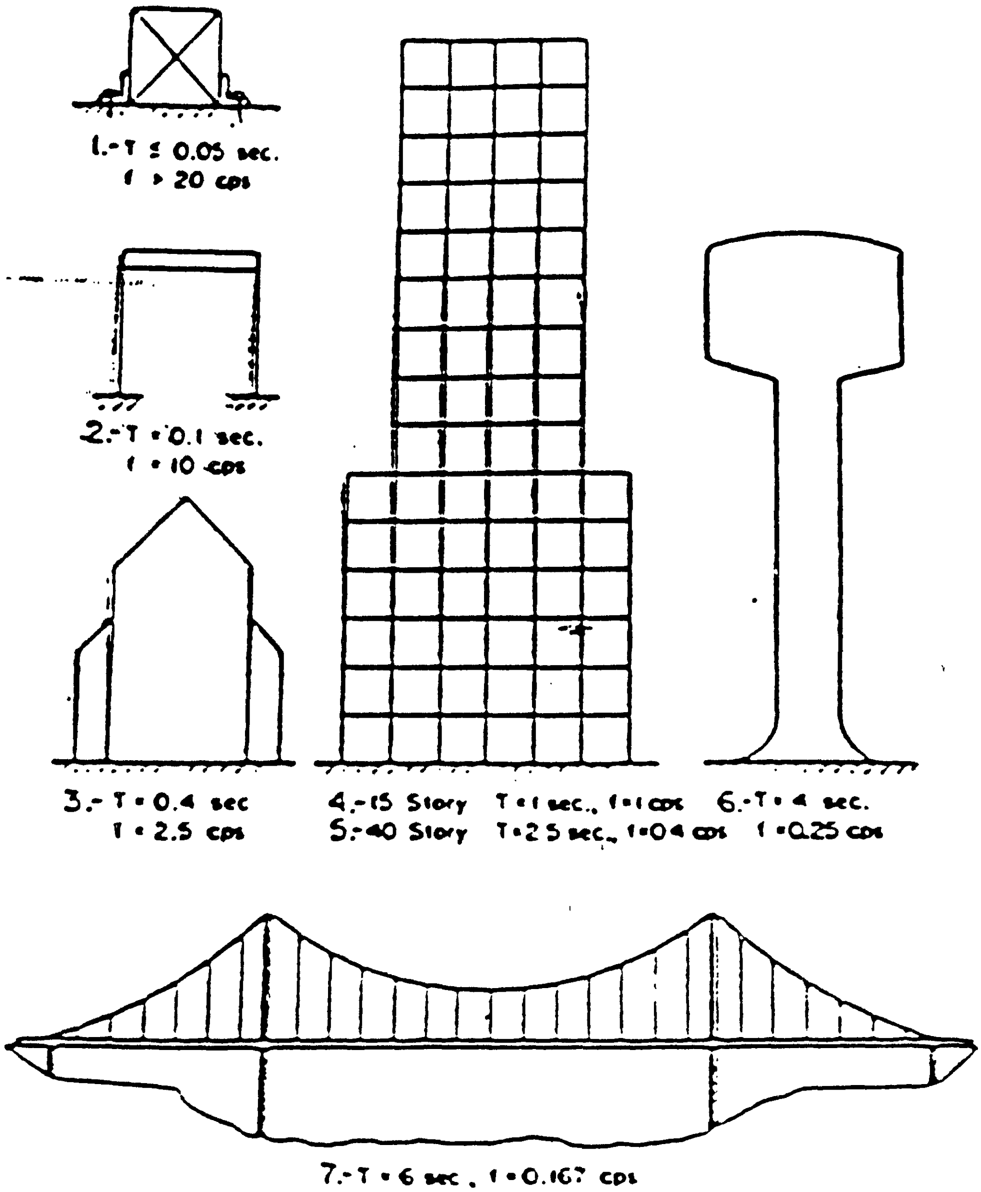
TECHNICAL JUDGMENTS ABOUT HOW BUILDINGS RESPOND TO GROUND MOTION

Question 6: Referring to the 5 percent damped horizontal response spectra below for the Holiday Inn ground motions, determine the spectral acceleration, spectral velocity, and spectral displacement experienced by each of the seven structures. The seven points on the spectrum refer to seven different types of structures shown on the next page.



Building Natural Period	1-2 Stories	3-7 Stories	> 7 Stories

The schematic illustration shown below gives the fundamental frequency (f_0) and fundamental period (T_0) for 7 classes of structures. Estimate the response of each class of structure to the ground motion accelerograms shown earlier by plotting the fundamental period of each structure on the spectrum. Number these points from 1 to 7.



Complete the Blanks Below

Structure	PGA	PGV	PGD	SA	SV	SD
1.	_____	_____	_____	_____	_____	_____
2.	_____	_____	_____	_____	_____	_____
3.	_____	_____	_____	_____	_____	_____
4.	_____	_____	_____	_____	_____	_____
5.	_____	_____	_____	_____	_____	_____
6.	_____	_____	_____	_____	_____	_____
7.	_____	_____	_____	_____	_____	_____

Where PGA = Peak Ground Acceleration

PGV = Peak Ground Velocity

PGD = Peak Ground Displacement

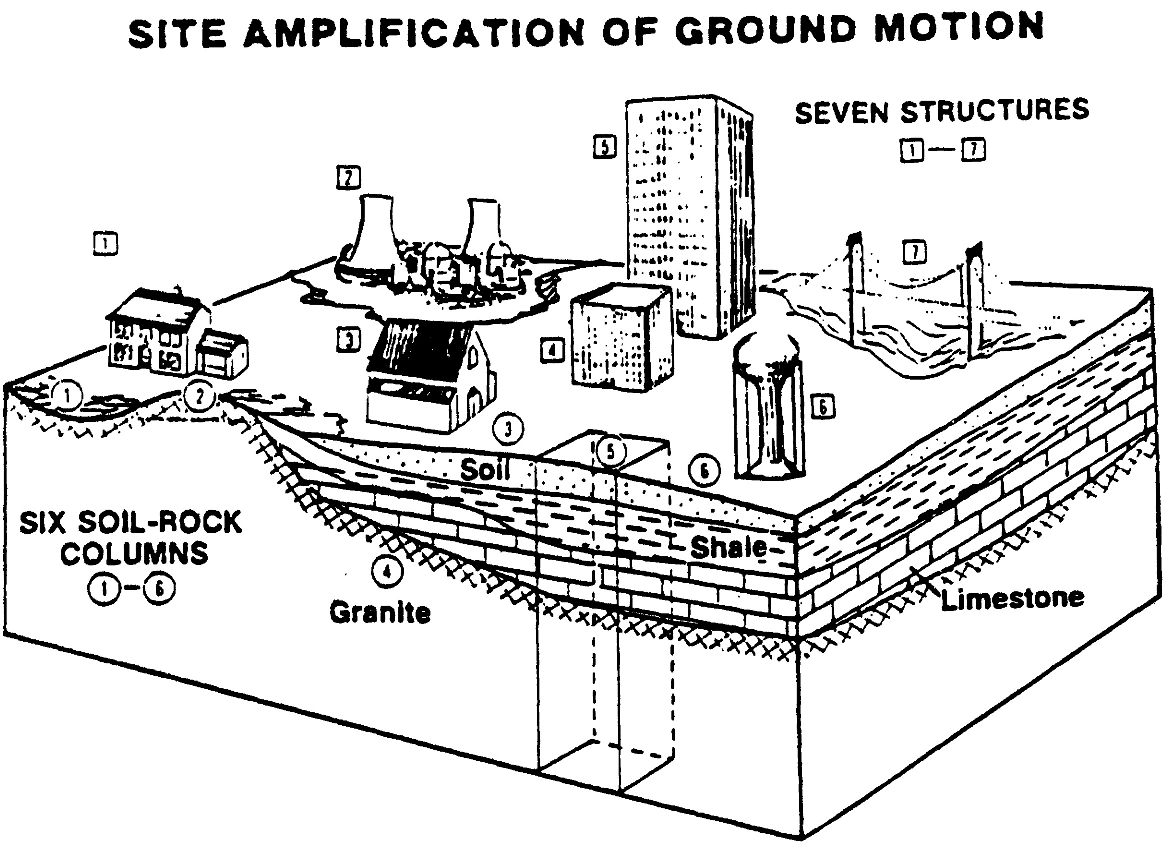
SA = Spectral Acceleration

SV = Spectral Velocity

SD = Spectral Displacement

Question 7: Soil Amplification of Ground Motion

Suppose you can select the site for the 7 structures shown in the figure below. You have have six sites to choose from.



Rank the sites in terms of relative site/structure compatibility for ground shaking. Best means site and structural periods are not similar; worst means they are similar.

STRUCTURE	BEST SITE	WORST SITE
1	________	________
2	________	________
3	________	________
4	________	________
5	________	________
6	________	________
7	________	________

TECHNICAL JUDGMENTS ABOUT THE GROUND SHAKING HAZARD AND RISK

Question 8: To assess the potential losses from earthquake ground shaking, the following information is needed:

1. A representation of the ground shaking hazard as a function of exposure time.

2. An inventory of buildings and facilities exposed to the ground shaking.

3. A representation of the ground motion-damage relation expressed as a percentage of replacement value for a range of building types.

Use the following graphs and those of preceeding questions to answer the questions below for <u>Memphis</u>:

A.

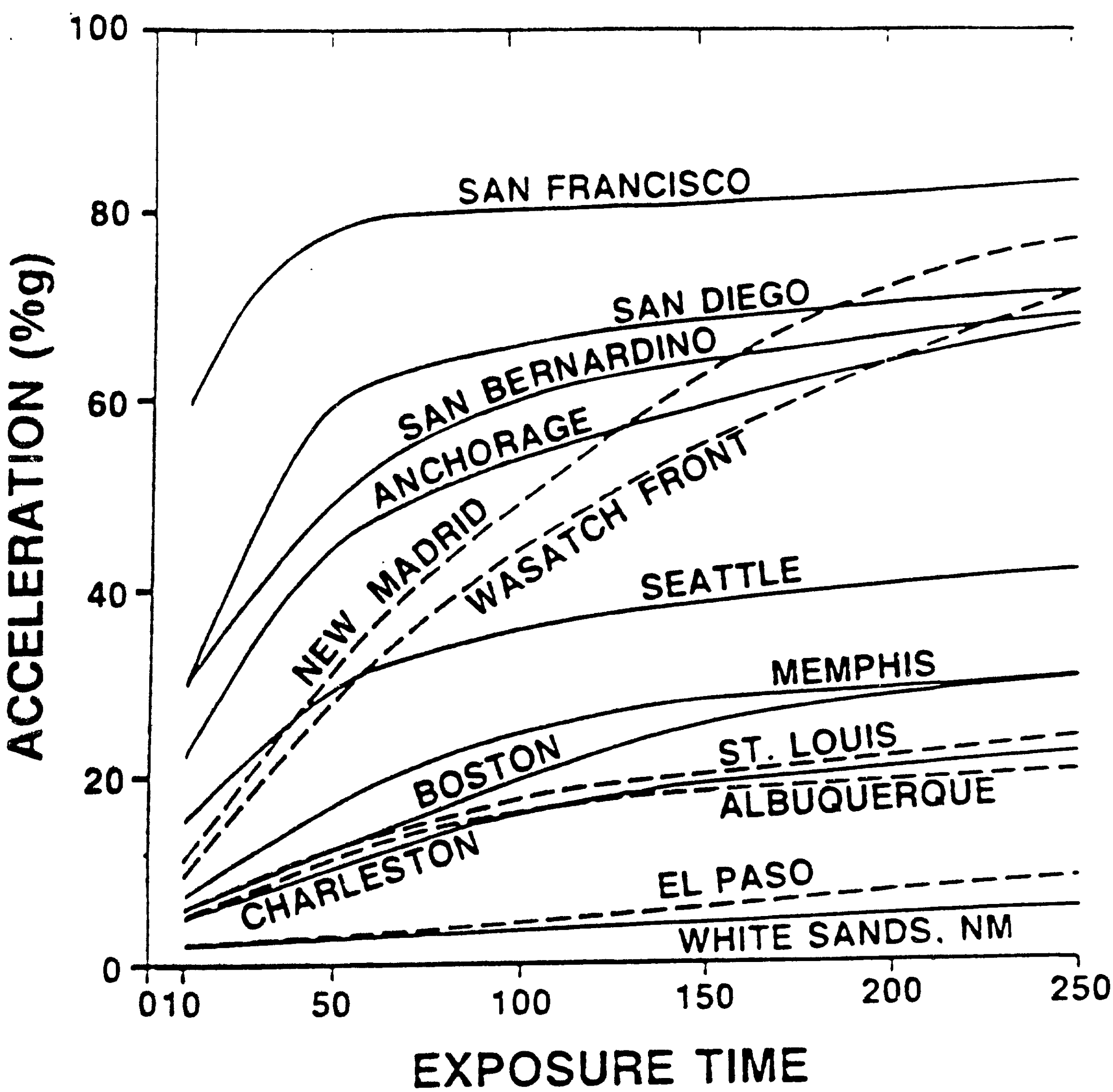
Exposure Time (Yrs)	Bedrock Acceleration	MMI
10	________	__
50	________	__
250	________	__

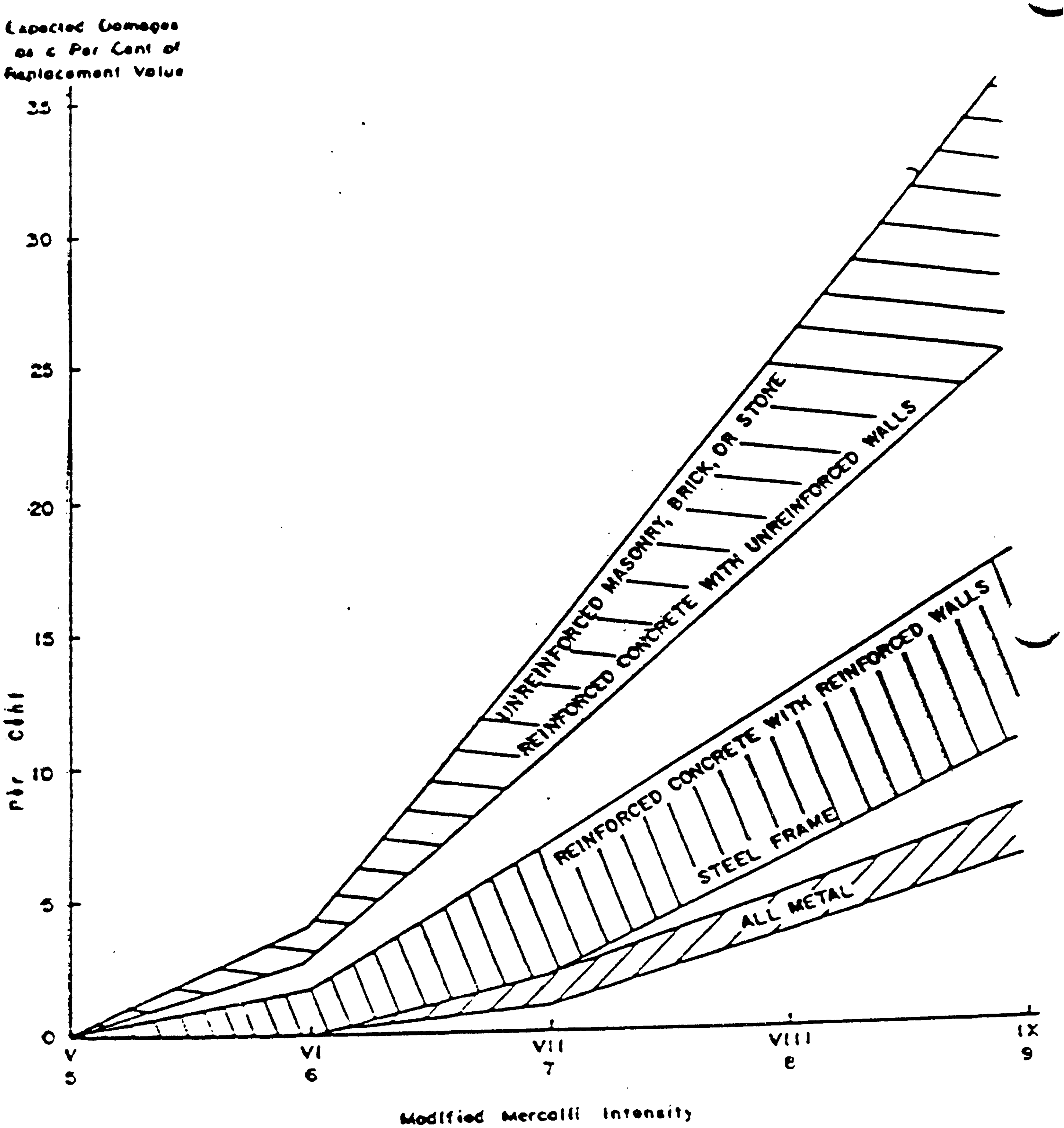
B. Assume unreinforced masonry construction, how may buildings have a replacement value of $1 million each would be in the inventory if the total loss was $1 billion in <u>the 50-year exposure</u> earthquake. Ground Motion? ______________________________

C. How much would the loss be reduced if the inventory of B were reinforced concrete buildings with reinforced walls instead of unreinforced masonry? ______________________________

D. What would be the loss in B and C if soil effects increased the intensity one unit? ______________________________

GROUND SHAKING HAZARD





Expected Damages as a Per Cent of Replacement Value
35
30
25
20
15
10
5
0
Per Cent
UNREINFORCED MASONRY, BRICK, OR STONE
REINFORCED CONCRETE WITH UNREINFORCED WALLS
REINFORCED CONCRETE WITH REINFORCED WALLS
STEEL FRAME
ALL METAL
V
5
VI
6
VII
7
VIII
8
IX
9
Modified Mercalli Intensity

Question 9: Typical "What If" questions that should be asked.

PHYSICAL PARAMETERS	EFFECT ON GROUND MOTION	RELATIVE SIGNIFICANCE
1. Location of Seismic Sources		
Faults	Zone of energy release	High
Typical Questions: What if all active faults are not identified? What if the seismic cycle of active faults is not known precisely?		
Source Zones	Affects level of shaking and spatial distribution of floating earthquakes	Medium
Typical Questions: What if the source zone is smaller than mapped? What if the source zone is really two smaller zones?		
2. Recurrence Rates		
Faults	Affects level of shaking and recurrence of upper bound earthquake	High
Typical Questions: What if the recurrence rate is longer than modeled in the exposure analysis? What if the recurrence rate is shorter than modeled?		
Source zones	Affects level of shaking and dependent on completeness and accuracy of historical seismicity	High
Typical Questions: What if the historical seismicity record is only complete for the last 80 years? What if large errors exist for epicentral and hypocentral locations?		
3. Attenuation	Affects level of ground motion at site.	Medium to high depending on uncertainity.
Typical Questions: What if the mean rate of attenuation is faster than modeled in the exposure analysis? What if the standard deviation in the mean value is larger than modeled?		
4. Local Site Conditions	Affects local response	Medium to high
Typical Question: What if anomalous (thin, thick) low velocity soil conditions exist?		

Question 10: Recognizing and Reducing Potential Vulnerability

The following schematic drawings illustrate a broad range of structural features one might see in a "windshield" survey of their community. For each drawing, analyze the situation and do the following:

A. In column A, state what man did wrong (e.g., siting near an active fault, etc.).

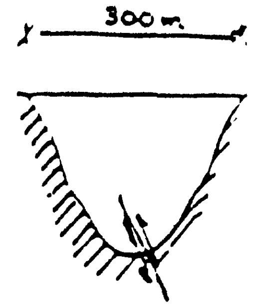
B. In column B, state which physical effects will probably cause damage (Note: Mitigation measures must be introduced to counteract these causative factors). Choose from:

1. Liquefaction.
2. Landslides.
3. Surface Fault Rupture.
4. Tectonic Deformation.
5. Seiche.
6. Ground Motion:
    a. Horizontal Motion.
    b. Vertical Motion.
    c. Duration.
    d. Spatial Variation.
    e. Development of Torsion.
    f. Development of Stress Concentrations.
    g. Site Amplification.

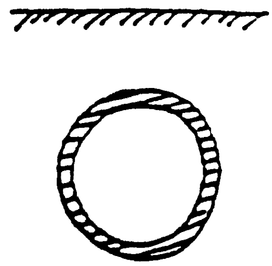
C. On the back, identify mitigation measures.

A	B	Situation

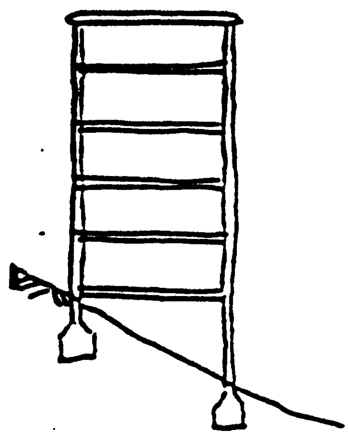
1. Dam with a fault in the foundation.



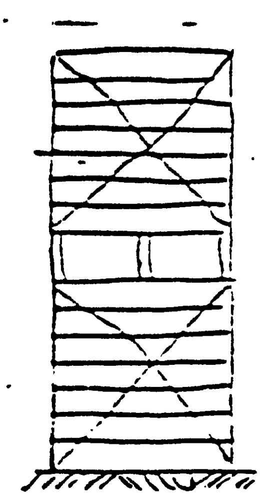
2. A long tunnel.



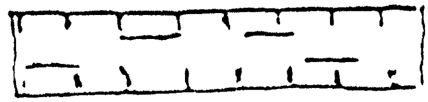
3. A building on a hill side.

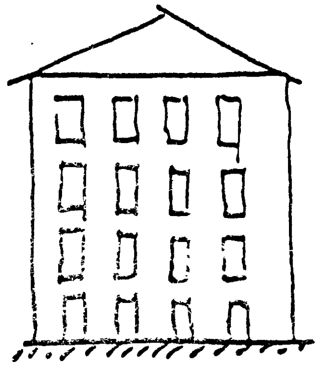


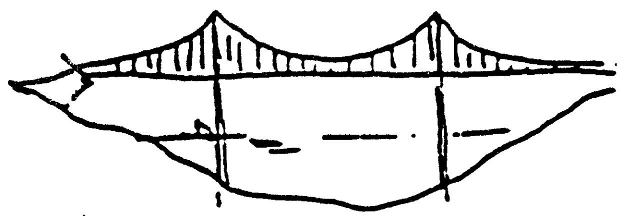
4. A building with a soft story at mid-height.

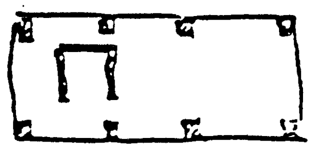


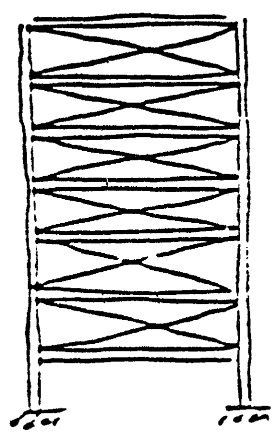
A	B	Situation
______	______	5. A very long building.
______	______	6. An unreinforced masonry building.
______	______	7. A suspension bridge.
______	______	8. A building without symmetry in plan.
______	______	9. A building with a soft story at the first floor.





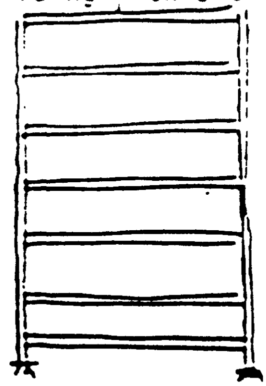




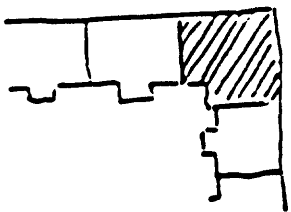


A	B	Situation
		10. A building with a short column.
		11. A building at the corner of a block.
		12. A smoke stack.
		13. A building having two elevations.
		14. A stadium roof.

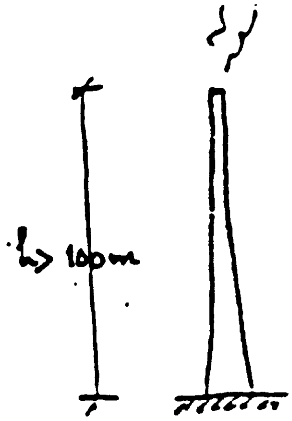
10. A building with a short column.



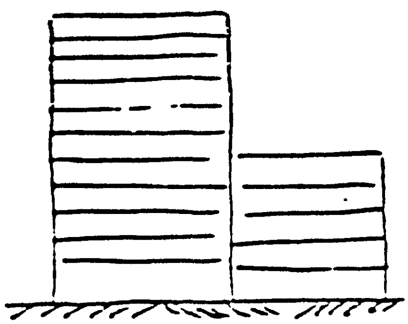
11. A building at the corner of a block.



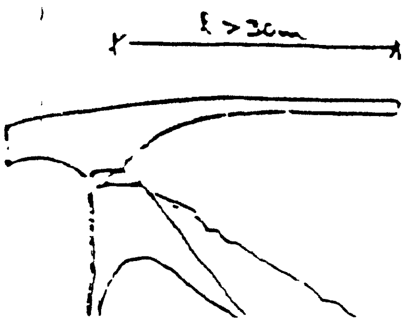
12. A smoke stack.



13. A building having two elevations.



14. A stadium roof.



LIQUEFACTION

TECHNICAL JUDGMENTS ABOUT EARTHQUAKE-INDUCED GROUND FAILURE

Question 11: Use a scale of 1 (most important), 2 (intermediate importance), and 3 (least importance) to rank the following physical parameters as to their capability to cause liquefaction at a site in an earthquake.

_____ a. Long active fault zone.

_____ b. Level of peak horizontal acceleration of 0.1 or greater.

_____ c. High-frequency ground shaking.

_____ d. Low-frequency ground shaking.

_____ e. Intermediate-frequency ground shaking.

_____ f. Long duration of ground shaking.

_____ g. Shallow water table at site.

_____ h. Shallow, young, fine grained sand deposits at site.

_____ i. Deep clay deposits at site.

_____ j. Irregular topography.

_____ k. Close to the epicenter (i.e., within 20 km).

_____ l. Far from the epicenter (i.e., 20-100 km).

TECHNICAL JUDGMENTS ABOUT BUILDING CODE ZONE MAPS

Question 12: The map below shows a zoning map proposed for use in a model building code to achieve earthquake resistant design. The meaning of each zone is approximately as follows:

Zone 0: Effective peak acceleration (EPA) of less than 5% g

Zone 1: EPA of 5 to 10% g

Zone 2: EPA of 10 to 20% g

Zone 3: EPA of 20 to 40% g

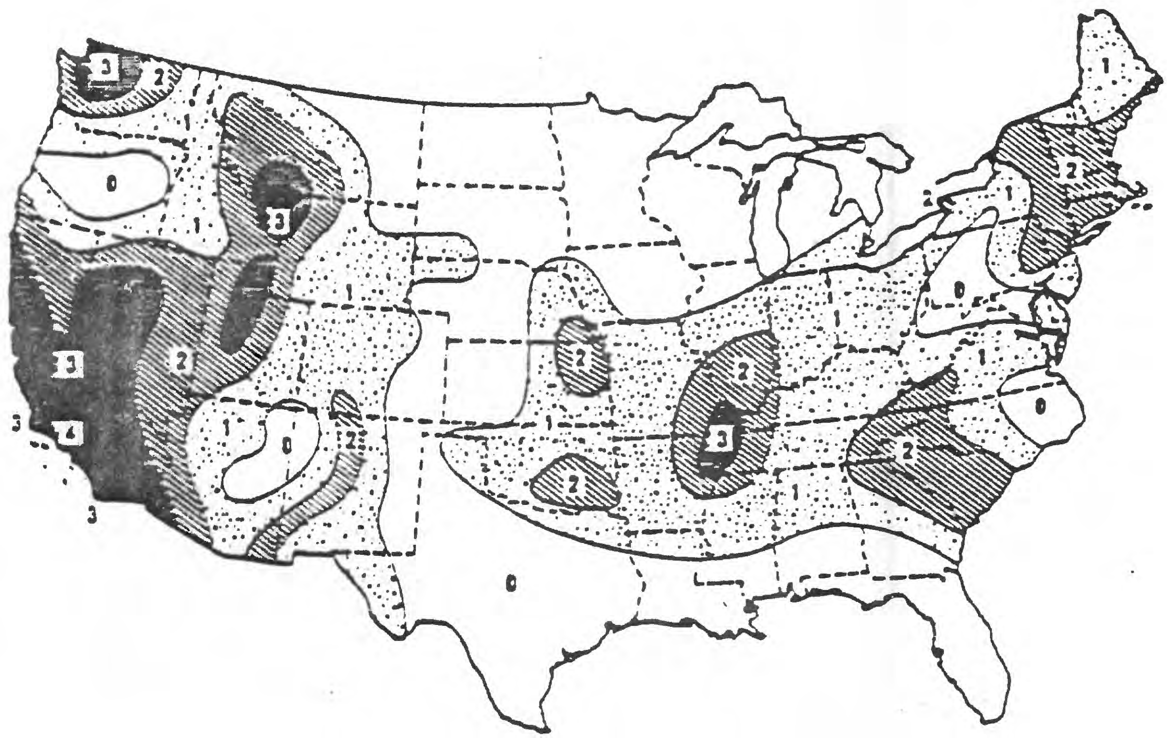
Zone 4: EPA of 40 to 80% g

Answer the following questions

1. What zone do you live in?

2. Which historic earthquakes govern the assignment in your zone?

3. What would be needed to change your zone?



SEISMIC ZONE MAP

Question 13: What physical effects should your community be planning for? What can be done in advance to mitigate each primary hazard?

Each natural hazard generates its own ensemble of physical phenomena (hazards) and sometimes one natural hazard will trigger the occurrence of another. The primary and secondary hazards of seven natural hazards are summarized below:

A. **Earthquakes** - The primary hazards are: ground shaking and permanent ground failure (landslides and liquefaction). The secondary hazards are: surface fault rupture, regional tectonic deformation, tsunamis, seiches, fire, flooding from dam failure, and aftershocks. (Note: the potential for very large sudden losses is the feature that distinguishes earthquakes from all other natural hazards).

Severity of ground shaking expected? ______________________________

Potential for landslides and liquefaction? ______________________________

Mitigation strategies? ______________________________

B. **Volcanic Eruptions** - The primary hazards are: pyroclastic flows and lahars, (i.e., mud flows generated by melting of snow and ice). Secondary hazards are: tepha, ash fall, lava flows, volcanic earthquakes, glacier bursts, floods, and sometimes tsunamis, famine.

Severity of pyroclastic flows? ______________________________

Potential for lahars? ______________________________

Mitigation strategies? ______________________________

C. **Windstorms** - The primary hazards are: storm surges, high winds, and floods. The secondary hazards are: lightning, hail, erosion, and scouring.

Susceptibility to storm surges? ______________________________

Susceptibility to flooding? ______________________________

Mitigation strategies? ______________________________

D. **Floods** - The primary hazards are: inundation from riverine floods, flash floods, and storm surges along the coast. The secondary hazards are: high water velocity, high waver levels, overtopping, erosion, and scouring.

Susceptibility to riverine flooding? ______________________________

Susceptibility to flash floods? ______________________________

Susceptibility to storm surges? ______________________________

Mitigation strategies? ______________________________

E. **Landslides** - The primary hazards are: falls, topples, slides, spreads, and flows of rock and soil. The secondary hazards are: debris dams, floods, and possible tsunamis.

Susceptibility to Landslides? ____________________

Mitigation Strategies? ____________________

F. **Tsunami** - The primary hazards are: inundation and wave impacts on strucutes. The secondary hazards are coastal erosion and scouring.

Susceptibility to Tsunamis? ____________________

Mitigation Strategies? ____________________

G. **Wildfires** - The primary hazards are: Encroachment on the community. The secondary hazards are inceneration, smoke, winds, fire storms, and erosion?

Susceptibility to Wildfires? ____________________

Mitigation Strategies? ____________________

GLOSSARY

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 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.

Attenuation. A decrease in seismic signal strength with distance which depends on geometrical spreading and the physical characteristics of the transmitting medium that cause absorption and scattering.

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.

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

Capable fault. A capable fault is a fault whose geological history is taken into account in evaluating the fault's potential for causing vibratory ground motion and/or surface faulting.

Design earthquake. A specification of the ground motion at a site based on integrated studies of historic seismicity and structural geology and 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. A design spectrum is typically a broad band specturm having broad frequency content. The design spectrum can be either site-independent or site-dependent. The site-dependent spectrum tends to be less broad band as it depends at least in part on local site conditions.

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 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. 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 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 value of peak ground acceleration considered to be of engineering significance. It can be used to scale design spectra and is often determined by filterng the ground-motion record to remove the very high frequencies that may have little or no influence upon structural response.

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

Exceedence probability. The probability (for example, 10 percent) over some exposure time that an earthquake 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 or facility is exposed to earthquake hazards. 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 earthquake hypocenter and the Earth's surface.

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 an earthquake, a nuclear explosion, 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 specially 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. The primary factors used to judge the potential for liquefaction, the tranformation of unconsolidated materials into a fluid mass, are: grain size, soil density, soil structure, age of soil deposit, and depth to ground water. Fine sands tend to be more susceptible to liquefaction than silts and gravel. Behavior of soil deposits during historic earthquakes in many parts of the world show that, in general, liquefaction susceptibility of sandy soils decreases with increasing age of the soil deposit and increasing depth to ground water. Liquefaction has the potential of occurring when seismic shear waves having high acceleration and long duration pass through a saturated sandy soil, distorting its granular structure and causing some of the void spaces to collapse. The pressure of the pore water between and around the grains increases until it equals or exceeds the confining pressure. At this point, the water moves upward and may emerge at the surface. The liquefied soil then behaves like a fluid for a short time rather than as a soild.

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 theoretically open ended, but the largest known earthquakes have had M_s magnitudes near 8.9.

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 naturally occurring, hard, consolidated material, located either at the surface or underlying soil. Rocks have a shear-wave velocity of at least 2,500 ft/sec (765 m/s) at small (0.0001 percent) levels of strain.

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 along 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 are believed to be similar in a given 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.

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.

PREPARATION FOR SURVIVIAL: PREPAREDNESS AND MITIGATION

I. Checklist of Actions to Make to Improve Preparedness and Mitigation

CIRCLE THE APPROPRIATE ANSWER: YES NO

YES NO 1. Has your organization conducted a structural and nonstructural vulnerability analysis of your buildings, facilities, and lifeline systems?

YES NO 2. Has your organization established educational and awareness programs?

YES NO 3. Has your organization emphasized the importance of a home preparedness plan so that if the disaster strikes while you are in the office, your family will be prepared?

YES NO 4. Has your organization made agreements with others (e.g., vendors and suppliers) to ensure continuity of operation?

YES NO 5. Has your organization developed inventories of critical supplies and equipment?

YES NO 6. Do you have a plan for maintaining critical employee skills?

YES NO 7. Do you have a plan for informing clients, the public, and media about your operations after an earthquake?

YES NO 8. Have you identified the vital records of your organization?

YES NO 9. Do you have a program for duplicating vital records and storing them off-site?

YES NO 10. Have you taken steps to protect your facility and equipment?

YES NO 11. Do you have backup facilities and equipment for your data processing needs?

PREPARATION FOR SURVIVIAL: RESPONSE

II. Checklist of Actions to Take to Improve Response Capability

CIRCLE THE APPROPRIATE ANSWER: YES NO

YES NO 1. Does your organization have plans for conducting initial damage assessments and identifying potentially dangerous situations?

YES NO 2. Does your organization have plans to provide continuous communications with employees (and other occupants) of your building(s), to provide hazard warnings, instructions, and announcements?

YES NO 3. Will emergency power be available to supply critical operations, processes, and emergency equipment?

YES NO 4. Have evacuation plans been developed and tested?

YES NO 5. Is there a plan to determine when it is safe to reenter an evacuated building?

YES NO 6. Have first aid and CPR courses been offered to employees?

YES NO 7. Does your organization have plans to provide for emergency housing, feeding, and non-medical care of employees (and other building occupants) for the critical 72 hour period after a disaster?

YES NO 8. Has someone been assigned responsibility for acting as liaison with the media to ensure that accurate information is provided?

YES NO 9. Has someone been assigned responsibility for incident commend?

PREPARATION FOR SURVIVIAL: RECOVERY

III. Checklist of Actions to Make to Improve Recovery

CIRCLE THE APPROPRIATE ANSWER: YES NO

YES	NO	1.	Has your organization established contacts with engineers and suppliers to perform clean up of potential building damage following an earthquake?
YES	NO	2.	Does your organization have plans for restoration of operations, maintaining essential operations, ensuring key personnel report to work sites, establishing temporary facilities or alternate headquarters, controlling access, etc.?
YES	NO	3.	Have you identified alternate sources of essential supplies and replacement parts in case normal vendors are unable to function after an earthquake?
YES	NO	4.	Have you developed post-earthquake financing strategies?
YES	NO	5.	Does your banker know your disaster contingency plan?
YES	NO	6.	Have you reviewed existing interorganizational mutual aid agreements to establish the range of possible needs following an earthquake?
YES	NO	7.	Have you made your perceived post-earthquake needs known to governmental and/or private sector organizations who might help to facilitate your recovery?

COURSE 2

PREPAREDNESS, WARNING, AND MITIGATION

A READER ON EARTHQUAKE HAZARD REDUCTION IN THE CENTRAL UNITED STATES

CONTENTS

II. PREPAREDNESS, WARNING, AND MITIGATION

Disaster Preparedness, Warning, and Mitigation

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Preparedness, warning, and mitigation are the cornerstones of a community's capacity to withstand the physical effects (e.g., ground shaking and earthquake--induced ground failure) generated in an earthquake.

Preparedness activities are initiated well in advance of the event in order to deal with the requirements of emergency managers during the response and recovery periods. They encompass the following:

- Development of a planning process to produce emergency response and recovery plans that are based on the best available scientific and technical data.

- Utilization of information gained from instrumental systems for hazard and risk assessment and warnings.

- Dissemination of information on the potential vulnerability of individual elements and infrastructure at risk in the community.

Warning includes activities that provide all sectors of the public with information on:

- **where** the event is expected to strike,
- **how** severe the impacts are expected to be,
- **how often** such phenomena are expected to occur, and
- **when** the next occurrence is expected.

Warning requires technical and societal components for successful implementation. Mitigation refers to those activities that are carried out in advance of a potential disaster, often as a consequene of peparedness planning or a specific warning, to reduce a community's vulnerability to damage and societal disruption.

Mitigation activities, like preparedness activities, are also carried out in advance of the event with the goal of reducing or preventing damage and societal disruption. They include:

- Development of realistic scenarios of potential losses and societal impacts for one or more possible events.
- Reduction of vulnerability to existing physical development in the community.
- Development of seismic zonation (i.e., the division of a region into areas expected to experience the same severity of a hazard).
- Enactment of land-use restrictions to avoid hazardous areas.
- Adoption and implementation of codes and standards for the siting, design, and construction of new buildings and lifelines (e.g.,

energy, water, transportation, and communication systems).

- o Adoption and implementation of criteria for the siting, design, and construction of important and critical facilities (e.g., facilities such as schools, hospitals, emergency command centers, nuclear power plants which are vital to the life of the community and must remain functional after an event).

Earth scientists, engineers, and social scientists build the knowledge base that practitioners use in preparedness and mitigation activities. The earth scientists and engineers address the physical nature of the earthquake hazards of ground shaking, earthquake-induced ground failure, surface fault rupture, regional tectonic deformation, seiches, flooding from dam failure, fire following earthquake, and the aftershock sequence. Their goal is to understand the physical system for each type of hazard, the parameters that control the cause and effect relations of the physical system, the central tendency and variability in space and time of each parameter, and the sensitivity to extrapolation of parameters beyond the limits of the data. Their focus is on answering the following basic questions:

- o Where have earthquakes happened in the past? Where are they occurring now?
- o How frequently do they occur? When will the next one occur?
- o How big have they been? How big can they be?
- o What kinds of physical effects have they caused? How severe have their impacts been? How severe could they be?
- o How have soils, buildings, and lifeline systems performed under these physical effects?

Social scientists address the social nature of a community's response to each earthquake hazard. Their goal is to understand human behavior, focusing on the following basic questions in the context of earthquake preparedness and mitigation:

- o How is knowledge produced and provided to practitioners?
- o How is knowledge disseminated between researchers and practitioners?
- o What factors control the utilization of knowledge?
- o How can collaboration between researchers and practitioners be enhanced?
- o How is the political will (using the existing corporate and police power) to achieve seismic safety developed in a community?

Experience has shown that knowledge alone makes no contribution to earthquake preparedness and mitigation if the knowledge base is:

- o unknown,
- o misunderstood,
- o inappropriate,
- o unintelligible,
- o misdirected, or
- o ignored.

EARTHQUAKE PREPAREDNESS

The goal in the Central United States is to improve emergency preparedness. The objectives are:

- o Identification of structures and facilities having special risks in each city.
- o Preparation of loss estimates in each city.
- o Preparation of functional multijurisdictional earthquake response and recovery plans.
- o Provision of training tailored to the needs of emergency responders.

EARTHQUAKE MITIGATION

The goal in the Central United States is to improve siting, design, and construction practices. The objectives are to:

- o Identify fault zones.
- o Identify areas expected to experience strong ground shaking.
- o Identify areas having soil deposits (e.g., linear clays) that can amplify ground motion.
- o Identify areas subject to ground failure (e.g., liquefaction and landslides).
- o Identify flood-hazard areas.
- o Idenfity high occupancy, hazardous buildings.
- o Identify procedures to reduce vulnerability through structural and non-structural.
- o Evaluate the 1988 editions of the seismic design provisions of the principal building codes (i.e, Southern, Uniform Building Code, and the NEHRP Recommended Seismic Design Provisions) and recommend adoption of the one that is most relevant.

LESSONS AND PERSPECTIVES ON PREPAREDNESS

Disasters are the ultimate test of a community's emergency response capability. A disaster reveals all of the weaknesses in the community's:

- o Disaster management structure.
- o Coordination within and between organizations.
- o People to people interaction.
- o Capability to execute tasks in a crisis environment.
- o Communication system.

These weaknesses, which may be completely unrecongized before the disaster, can be corrected through a planning process that utilizes all of the knowledge gained from past disasters of all types both in the community and in other communities throughout the world. The key is comprehensive integrated planning.

Disasters triggered by natural hazards, although relatively rare when compared with other phenomena, are an important consideration for every community. Insight into the problems they pose for disaster preparedness planning has been gained from occurrences such as:

- o Earthquakes: 1964 Prince William Sound, Alaska, 1985 Mexico, and 1988 Spitak, Armenia, and 1989 Loma Prieta, California.
- o Volcanic Eruptions: 1980 Mount St. Helens, Washington and Nevado del Ruiz, Columbia in 1985.

- o *Floods*: Bangladesh in 1970 and 1988.
- o *Hurricanes*: Hurrican Agnes in 1972, Hurricane Gilbert in 1988, and Hurricane Hugo in 1989.
- o *Tornadoes*: The Palm Sunday outbreak in Iowa, Illinois, Indiana, Michigan, and Wisconsin in 1965 and the super outbreak of tornadoes that struck 11 Midwestern States and Canada in 1974.
- o *Landslides*: The Mamayes, Puerto Rico landslide of 1983.
- o *Tsunamis*: The Chilean earthquake--tsunami which struck Hawaii and the coasts of almost all of the Pacific rim countries on May 22, 1960.
- o *Wildfires*: The great Yellowstone wildfires of summer 1988.

Case histories of these events are available in the literature.

A disaster is the ultimiate test of a community's emergency response capability.

Disasters pose unique problems which are not experienced in day-to-day emergency management. A disaster reveals the differences in:

- o Management Structure
- o Coordination
- o Interaction
- o Tasks and Procedures
- o Communization
- o Terminology
- o Press
- o Roads, Communications, and Critical Facilities

There is a major paradox in disaster preparedness. It is that the Federal Government pays for most of the damages, but local governments are most likely to have responsibility for the response. Also, the responsibility for planning is in the public sector but the resources are mainly in the private sector.

Public apathy is a major problem in disaster preparedness. Disaster preparedness is usually low on a community's list of priorities,

-- BECAUSE --

-- The risk of a natural hazard disaster is low

  - o 1 fatality in 100 billion person hours of exposure;

-- whereas the corresponding risks from smoking and motor vehicle transport are, respectively,

- o 5 in 10 billion and
- o 1 in 1 billion.

Reduction in public apathy is proportional to the *recency* and *severity* of the last disaster. The key elements causing change are:

- o Liability.

- o Public Awareness.
- o Recent Experiences.

Recounting and evaluating recent disasters are essential actions for improving a community's disaster preparedness. However, recounting and evaluting are like writing the account of a battle. A typical person in a battle usually knows only what is happening one hundred yards on each side. For this reason, the most accurate post-disaster audit will be based on the integrated experiences of more than one person.

Between 1865-1928, the Nation has experienced large-scale disasters from a steamboat explosion, a forest fire, a flood, two hurricanes, a fire on a steamship, and an earthquake and accompanying fire. Each of these seven disasters caused more than 1,000 deaths, the criterion for a large-scale disaster.

The most effective disaster planning is based on:

- o Events for which knowledge can be extrapolated, and
- o Realistic events of moderate size having a variety of coordination problems.

However, one of the basic rules in disaster preparedness is:

- o The planning process is much more valuable than the written plan.

Having a plan sometimes creates the illusion of being prepared. However, preparedness is achieved only when the plans are:

- o Tied to training.
- o Based on valid assumptions.
- o Keyed to the necessary resources.
- o Acceptable to the users (this happens in the planning process).

Plans fail if a person knows only their own role, but plans succeed when everyone knows how their role interfaces with the roles of others.

Plans fail when they are based only on the "correct behavior" of people, but plans succeed when they are based on the "likely behavior" of people.

Experience has shown that disasters are characterized by:

- o Great uncertainty in the type and extent of damage.
- o Initial actions which are based on inaccurate information.
- o Needs which change rapidly as information improves.
- o Organizations which are slow to share information.

Disasters almost always:

- o Trigger new damands.
- o Require sharing of resources.
- o Attract new partners.
- o Pose jurisdictional problems.
- o Render traditional roles and tools useless.

- Result in new organizations.

The information needs in a disaster change rapidly with time. At the beginning, the priority is for information on:

- The consequences and the appropriate countermeasures.

Subsequently, the needs include:

- The resources available for implementing the countermeasures.
- The priorities and knowledge of how resources have been allocated.
- Feedback from people and organizations.

Disasters have both a tragic side and a bright side. The bright side is associated with the opportunities a disaster provides to learn and to gain political support for mitigation. Learning is enhanced by developing integrated case histories of:

- disasters in the community, and
- other community's disasters.

Disaster preparedness is critically important for every community.

Planning Considerations for Earthquakes

Some of the broad physical aspects of earthquakes will be reviewed as an illustration of some of the basic concepts of preparedness planning. An earthquake, depending on its magnitude, proximity to an urban center, and the degree of earthquake disaster prevention and preparedness measures implemented in the urban center, can cause a disaster. The September 19, 1985, Mexico, December 7, 1988, Spitak (SSR), and October 17, 1989, Lomas Prieta, California earthquakes are recent examples of earthquake disasters. Earthquakes are probably the worst single natural hazard the Nation must face in terms of potential loss of life, property damage, and societal impacts. Except for California, no region of the Nation is adequately prepared yet for the potential disaster a moderate- to great-magnitude earthquake (i.e., magnitudes ranging from 6 to greater than 8) could cause.

When devising and implementing disaster prevention and preparedness measures in the Eastern and Western United Sates, one must be aware of important differences in the physical effects of ground shaking, surface fault rupture, earthquake-induced ground failure, tectonic deformation, and tsunamis accompanying an earthquake. These differences are summarized below:

1. <u>Ground Shaking</u> - In terms of peak acceleration, earthquake ground shaking in the East for a given exposure time such as 50 years (the useful life of an ordinary building) ranges from less than 10% to about 50% of the level expected in California. In the East, ground motion attenuates relatively slowly away from the epicenter and at large epicentral distances, because of dispersion, it is characterized by long duration and is rich in low frequencies. These characteristics of the ground shaking in the East have been recognized as a possible source of damage to tall buildings located a few hundred miles from the epicenter which are potentially

susceptible to long-duration, low-frequency ground shaking.

2. Surface Faulting - Except for the 1811-1812 New Madrid earthquakes in the Central United States, no historic earthquake has caused surface faulting in the East. On this historical basis, this phenomenon is not expected to happen. In contrast, almost all historic surface faulting in the West has occurred in earthquakes of about magnitude 5.5 or greater on faults that exhibit geologically young displacements (i.e, displacement occurring within the last 10,000 to 2 million years).

3. Recurrence Interval - The recurrence interval of magnitude 8 type earthquakes on the San Andreas fault system is in the order of a century; whereas the recurrence interval for similar sized earthquakes on the New Madrid Seismic Zone is much longer and in the order of five to seven centuries.

4. Ground Failure - The slow rate of seismic wave attenuation and the large area of long-duration ground shaking in the East increase the potential for triggering ground failures over a broader area than in the West. Liquefaction, in particular, is likely to be widespread in the East.

5. Ground Motion Amplification - Soil columns in both the East and West appear to have physical characteristics that can cause amplification of ground motion in selected frequency bands, such as in Mexico City. Locations in San Francisco, Los Angeles, Salt Lake City, Memphis, Boston, and Charleston have been identified in past studies.

6. Regional Tectonic Deformation - This phenomenon, which can result to substantial changes in elevation, is a characteristic feature of earthquakes having magnitudes of 8 or greater. Regional tectonic deformation has occurred in both the East and the West (for example, in connection with the 1811-1812 New Madrid earthquakes and the 1964 Prince William Sound, Alaska earthquake).

Thirteen broad assumptions are typically made when developing a community earthquke disaster preparedness plan. They are described below to facilitate comparison with other natural hazards:

1. Warning - Because the science of earthquake prediction is not sufficiently mature to provide reliable short-term warning prior to a moderate-to-great magnitude event, earthquakes of this size are assumed to strike the community without warning.

2. Scenarios - A worst-case scenario is one of several scenarios used for planning purposes. The assumption is often made that an earthquake of about the same size as one that had occurred in the past will recur at the location and time of day that will produce the maximum destruction and number of casualties in the community.

3. Impacts - For planning purposes, the most densely populated parts of the community having hotels, apartments, condominiums, and office buildings are assumed to suffer the greatest damage, highest losses,

and most casualties.

4. Physical Effects - Preparedness planning is typically developed for: a) ground shaking, b) earthquake-induced flooding, c) earthquake-induced landslides (including lateral spreads and debris flows), and d) liquefaction). Fire is also assumed to occur after the earthquake and a long aftershock sequence.

5. Aftershocks - Aftershocks are expected to occur for months and to trigger collapse of structures previously damaged or weakened in the main shock.

6. Societal Disruption - The physical, emotional, and social impact on the populace is assumed to be varied and complex. Considerations include: separation of family members, people trapped in collapsed structures, and people trapped on damaged roadways or in huge traffic jams between the home and the school or the work place.

7. Transportation Lifelines - Movement into and from damaged areas is assumed to be severely hampered for days to weeks.

8. Convergence - Post-disaster convergence is assumed to occur. Many investigators from many regions of the United States and foreign countries will come to observe and to conduct on-site investigations.

9. Communication - Communication is assumed to be severely disrupted or destroyed for hours to weeks.

10. Initial Response - It is assumed that the State will initiate the disaster response.

11. Local Resources - It is assumed that city and county resources will not be adequate.

12. Assistance to Individuals - It is assumed that individuals in the community will be on their own for about 72 hours.

13. External Assistance - It is assumed that within 72 hours after the event, it will be possible to bring the maximum available Federal, State, county, and city response forces and resources to bear on the problem.

Lessons and Perspectives on Warning

The seismic cycle is a basic concept that is very important for both earthquake warning (prediction) and mitigation (loss reduction). Prediction is based on the fact that earthquakes are generated in recurring cycles as stress accumulates and is released along faults. In Alaska, California, and the Pacific Coast, regeneration of stress along faults results from differential movement between the Pacific and North American plates (i.e., interplate tectonics). This phenomenon, which occurs at the rate of centimeters per year, has persisted over millions of years. The stress accumulation in other parts of the United States (e.g., the Mississippi Valley Region) is more subtle because the stress accumulates as a function of intraplate tectonics. In general for both tectonic environments, recurrence of large-to-great magnitude earthquakes (i.e., magnitudes of 7 and greater) is on the order of several decades to several hundred years with the frequency being much higher in Alaska and California than in the remainder of the United States.

When the seismic cycle is several decades or more for the recurrence of large-to-great magnitude earthquakes, mitigation actions must overcome public apathy. A community can (and often does) use one set of facts about the issue as its justification for failure to adopt seismic safety policies; namely the fact that:

- o earthquakes are low-probability events,

while ignoring the other set of facts, namely:

- o earthquakes have a high probability for causing a disaster, especially when the community is unprepared and has not implemented realistic loss-reduction measures.

Hence, mitigation actions are often postponed by a communicty until after it experiences a disaster, or until the disaster strikes close enough to home to awaken its will to act.

There are 10 basic ways to take the earth's pulse. The objective of earthquake prediction is to make a scientific statement about the probability of occurrence, magnitude, location, and time of a future earthquake in a way that the various sectors of the public can use.

Monitoring of precursory phenomena is accomplished by making scientific measurements of a fault system with one or more of the following:

- o Laser-ranging instruments.
- o Surveyor's level.
- o Gravimeters.
- o Strainmeters.
- o Creepmeters.
- o Seismeters to monitor seismicity.
- o Resistivity gauges.
- o Scintillation counters.
- o Tiltmeters.
- o Magnetometers.

Every community may not have access to all of these sensors. In all cases, for each sensor, measurements must be made over a period of a decade or more to acquire enough information to distinguish the signals of precursors from the background noise.

The probabilities of a magnitude 7-type earthquake on the San Andreas fault system have been determined for the period 1988-2018.

The Parkfield area has the highest probability (nearly 100 percent chance of occurrence) and an official predition of a magnitude 6.25 earthquake has been provided to officials in California. The center of the 6-year time window is January 1988. Precursors in Parkfield are being measured continuously on an extensive array of instruments.

The probability of a magnitude 7.0 type earthquake is greater in southern California than northern California for the period 1988-2018. One should remember that the probability of a large earthquake along the entire length of a fault system is higher than the probability for any of the fault's constituent segments for a given period of time.

In northern California, the probability is:

- 50 percent for the occurrence of a magnitude 7 earthquake.

In southern California, it is:

- 50 percent for a occurrence of a magnitude 7.5 earthquake.

The scientific community has learned an important lesson from past earthquakes (e.g., the 1988 Spitak earthquake). This lesson is:

- Earthquake prediction and warning have limited value if the societal component of the process is not as well developed as the technical component.

The earthquake prediction program of the U.S. Geological Survey in the National Earthquake Hazards Reduction Program has emphasized both the technical and societal components. The message, which is critically important, must be:

- specific,
- clear,
- accurate,
- certain, and
- consistent

with respect to the:

- location of the predicted event,
- time of its expected occurrence,
- risk, and
- guidance for coping with the physical effects expected to impact people and the community.

Guidance contained in the message conveying a prediction can facilitate community decisionmaking regarding actions such as:

- Lowering the level of water behind dams.
- Placing disaster response equipment in safe locations.
- Reducing fire hazards.
- Planning to cope with disruptions in transportation routes.

Many other loss reduction actions can be triggered by an earthquake prediction.

Lessons and Perspectives on Mitigation

Risk (exposure to a change of loss) is inherent in every community because of the earthquake threat. Doing nothing contains the elements of risk.

Mitigation of risk involves:

- o Gaining time to resolve uncertainties.
- o Gaining information on cause and effect relations.
- o Gaining control over possible losses (e.g., reducing vulnerability to hazardous buildings, etc.).

Earthquake mitigation requires an integrated analysis of the models for:

- o earthquake hazards(i.e., ground shaking, ground failure, surface fault rupture, dam break, seiches, fire),
- o exposure, and
- o vulnerability.

This analysis yields an assessment of the chance of loss.

Loss-reduction measures are then devised as countermeasures to reduce the risk to the community.

A Community has both technical and societal strategies available for mitigation. They include:

TECHNICAL

- o Identification and advoidance of hazardous sites during the physical development of the community.
- o Planning and building to withstand the physical effects (hazards) generated in an earthquake.
- o Issuing alerts and warnings (predictions) of future earthquakes to the populace.

SOCIETAL

- o Emergency preparedness planning.
- o Undertaking damage control (e.g., reduction of vulnerability to hazardous buildings) and mitigation measures to counteract the effects of ground shaking, earthquake-induced ground failure, surface fault rupture, and tectonic deformation (i.e, the earthquake hazards).

The essential elements are:

- o Hazards Information.
- o People trained to use the information.
- o Programs to apply loss-reduction measures.

Those who collect and analyze the technical information should seek to provide explicit answers to the following questions about each physical effect:

- o Where?
- o Why?
- o How often?
- o How severe?
- o When?

However, knowledge that is unknown, unavailable, ignored, or misused is worthless to a community. Thus, translation and dissemination activities are needed.

Translation of technical information into reports and maps that can be applied by users other than scientists and engineers is critically important if knowledge is to be transformed into loss-reduction measures in a community. "Translated" means that the reports and maps answer the explicit questions stated above.

Dissemination and communication of translated reports and maps to agencies and individuals who have a need for them is the next critical step in the process. Dissemination is much more than mailing a document; it requires interaction within and between researcher and pracitioner networks.

Use of translated and disseminated information in selected loss-reduction techniques considered to be appropriate for the community at that point in time is the next step. These techniques can be regulations, policies, and programs.

Evaluation of the effectiveness of the loss-reduction techniques selected by community decisionmakers for application in the community is the next step in the process. Evaluation is typically made after the regulations, policies, and programs have been in use for a period of time.

The outcome of evaluation can range from additional research to close gaps in fundamental knowledge to legislation to modify or improve the enforcement of the loss-reduction measure.

Training is an essential part of the process of mitigation. Effective training must:

- o Address the technical-societal-political issues of the region.
- o Focus on essential research results needed to advance the state-of-knowledge and state-of-practice.
- o Develop local multidisciplinary expertise for implementing the loss-reduction measures.

Loss-reduction measures include:

- o Increasing the awareness of earthquake hazards in all sectors of the public (e.g., scientists, engineers, architects, planners, developers, insurors, emergency managers, public officials, policymakers, and citizens).

- Studies and plans for developing the land.
- Design and construction practices to ensure life safety and/or building function.
- Policies for discouraging or removing hazardous development of the land.
- Regulation of land development.
- Vulnerability studies.
- Plans for disaster preapredness, response, and recovery.

Certain factors exist in every community which can become a hinderance to any or all of the mitigation actions listed above. They include:

- Higher priorities (before the disaster).
- Political and economic costs outweigh the perceived benefits of mitigation.
- The complexity and uncertainty of earthquake hazards.
- Lack of the required technical and administrative capabilities to implement or monitor mitigation actions.
- The complexity of inter-governmental and inter-orgnaizational relations inherent in the required actions

Conclusions

In the face of reality represented by the wide variety of hinderances to preparedness, warning, and mitigation, a community must devise a policy that will move it incrementally through the period of integration--

- the period of time where problem situations, policy considerations, and political considerations are worked out in concert.

to the period of implementation--

- the period of time when the community invests its resources to policies into actions that lead to seismic safety.

The windows of opportunity that facilitate movement from one period of activity to the next is usually the occurence of a damaging earthquake, either in the community or in other communities which become surrogates. A damaging event provides the opportunity for community leaders to call for change in existing seismic safety policies and to advocate specific loss-reduction measures.

What Can Communities Do?

Decisionmaking to avoid or to reduce losses from earthquake hazards is restricted by economic, social, and public policy factors. The principal restraint is stated by the question, "How much will it cost?" If a community decides to attempt to reduce losses from earthquake hazards, its planners and decisionmakers must face the possibility of increased costs and decide what actions are conservative and prudent.

As communities accept the premise that costs associated with specific loss-reduction actions sluch as avoidance, land-use zoning, engineering design, and insurance are prudent, the question that will be asked is, "How much are we willing to pay?" An initial requirement for answering this question is for the community to determine.

- o The physical causes of each natural hazard and the probability of each hazard occurring locally.
- o The current local annual loss and the potential for suddenloss from each hazard.
- o The local distribution of levels of relative severity expected from each hazard.
- o The potential loss as a function of time and loss-reduction actions.

What Is the Benefit-Cost Ratio of Reducing Losses from Earthquake Hazards?

No widely accepted method exists for determining benefit-cost or risk-benefit ratios for specific loss-reduction actions. The following excerpt from **The Nature, Magnitude, and Costs of Geologic Hazards in California and Recommendations for Their Mitigation** (1973) provides some insight into benefit-cost analysis of the ground shaking hazard:

> Given a continuation of present conditions, it is estimated that losses due to earthquake shaking will total $21 billion (1970 dollars) in California between 1970 and 2000. Most of damage and loss of life will occur in zones of known high seismic activity; structures that do not comply with the Field and Riley Acts, passed in 1933, will be especially vulnerable. If the present-day techniques for reducing losses from earthquake shaking were applied to the fullest degree, life loss could be reduced up to 90 percent, the total value of losses could be reduced by as much as 50 percent. Total costs for performing the loss reduction work would be about 10 percent of the total project loss, which with 50 percent of effectiveness provides a benefit to cost ratio of 5:1.

According to Terry Margerum (1980), "for most geologic hazards, the loss amount is generally reduced well over 90 percent when construction codes are applied."

Development of preparedness, warning, and mitigation is a long-term process for every community, usually requiring a decade or more for full realization.

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SCENARIO ON RECOVERY ISSUES[1]

1 Presented at the annual meeting of the Society of Chartered Property and Casualty Underwriters, October 18, 1989.

The Event

A 7.5 magnitude earthquake struck Los Memphis, Missouriana, a city of 1.7 million people, at 7:32 a.m. on September 19, 1989. The quake, which lasted between 25 and 35 seconds, caused a ten foot horizontal displacement of the earth and resulted in high liquefaction and ground failure. It was followed by more than 100 aftershocks.

Much of the downtown area was destroyed and the streets, jammed with rush hour commuters, were buried under 7 ft. of debris and broken glass. Fires in the downtown and residential areas raged uncontrolled for more than 72 hours.

The entire infrastructure was substantially damaged, including ruptured water mains, gas mains, sanitary, and storm sewers. Bridges and overpasses collapsed. Highway ramps and approaches, constructed on fill, were destroyed. Two hospitals collapsed, nine others are in danger of falling. While the main power plant survived, much of the distribution system was destroyed. Emergency power was exhausted in 24 hours.

Ten thousand people died and nearly 160,000 were injured, 30,000 of whom required hospitalization. The coroner's office was overwhelmed. Seriously injured people were transported to medical facilities in other states. The quake immediately displated 500,000 people, but destruction of power, water, and sanitary facilities and other factors ultimately increased this figure to 1.2 million. There were 100 hazardous material spills, 12 of which were very serious. Mass care facilities were established in state and national parks. However, many of the victims have now emigrated to temporary living with friends and relatives in other states. The federal government brought in tens of thousands of people to assist state and local government.

Scenario

It has now been four weeks since this devastating earthquake. While the essential needs of shelter, food, clothing, and sanitation have been provided to the catastrophe victims, it appears that little has been done to restore the community. The state legislature, the governor, and a number of United States congressmen have expressed outrage over the lack of response beyond the initial emergency.

The governor has ordered public hearings to identify the causes of the delay.

We join this hearing which is in progress.

The hearing officer is Frank Nutter, who is interviewing engineer, Walter Hayes, Dr. William Petak of local government, and Jerry O'Kane from the insurance industry.

You, the audience, are part of this scenario representing the public, the media, the homeowners and businessowners of the community. After the initial interviews, you, as victims or observers of this catastrophe will be invited to pose your questions.

Frank Nutter: Dr. Petak, the fires have all been extinguished, the smoke has cleared, and the situation has been stabilized for a couple of weeks now. You have had an opportunity to tour the area and consult with your experts. In your view, what are the direct economic effects of this disaster?

Dr Petak: It is almost impossible to estimate at this point because we don't have a clear handle on the full scope of the damage. The mere fact that a building is standing does not mean that it can be saved. Every building, bridge, overpass, and other structure in the city must be inspected before a final amount can be reached. As a guess, the cost to replace the destroyed buildings and their contents - including private as well as federal, state, and local government buildings - could run $70 billion.

Frank Nutter: $70 billion in direct damage! Can you describe for us some of the indirect effects?

Dr. Petak: I suspect that the indirect consequences of this earthquake are going to be even more costly than the direct impact. We are looking at at least 500,000 of our citizens displaced so mass care costs will be substantial. City services are frankly overwhelmed. Fire fighting and other emergency equipment that survived the disaster have been virtually run into the ground. We have no count of the numbers of businesses destroyed or rendered inoperative from the lack of electricity, water, sanitary facilities, or telephones. Our transportation system is totally disrupted. Even businesses that can continue to operate have no customers unless their product or service is essential to survival. It will be months, or maybe years, before the business environment is restored. Employment, of course, is dependent on business. Without functioning businesses, there is no employment. But, beyond the local scene, this city is not an island, but is interdependent with other regions of the country through governmental, trading, and employment relationships. Our banking industry is also interdependent and the damage and economic impact on our local banks will affect financial institutions all over the country. Our airport is only marginally operative, we have no railroad passenger or freight service, vehicular traffic will be disrupted for months, computer communications are almost nonexistent - the list goes on and on.

Frank Nutter: Clearly, the insurance industry must play a vital role in the restoration of this community. Mr. O'Kane, can you estimate the amount of this damage that will be covered by insurance?

Jerry O'Kane: Only about 5% of the public have been persuaded to buy earthquake insurance, so much of the shake damage will not be covered. Our preliminary evaluation, however, is that the direct shake damage amounts to only about 25% of the total. Fire ensuing earthquake is routinely covered under property insurance policies. Motor vehicles are covered as is workers compensation, general liability, and several other areas. The insurance industry's involvement will be substantial.

Frank Nutter: From what you have said then, insured damages could amount to $50 billion, correct?

Jerry O'Kane: That is correct.

Frank Nutter: Can the insurance industry withstand a $50 billion payment?

Jerry O'Kane: Yes, but not very easily. This will amount to about half of the industry's surplus. But, what will be more devastating is the total economic impact.

Frank Nutter: What do you mean?

Jerry O'Kane: To pay these claims, insurers will need to liquidate assets. Much of this is currently in municipal bonds. This is going to create havoc in the financial markets. Secondly, this disaster will force some insurers into insolvency. While through the state's insurance insolvency mechanism, those company's claims will be covered by others, the assessments may well trigger other companies into insolvency. Finally, the ability of insurers to write new business is controlled by their surplus. The industry's ability to assume new business will be substantially impaired.

Frank Nutter: The message I am getting from both Dr. Petak and you, Mr. O'Kane, is that the entire nation will suffer from this earthquake.

Jerry O'Kane: Very definitely.

Frank Nutter: The very business of the insurance industry is to assume risks and to prevent the serious economic impact of unpredictable and unforeseen events. Why is it that the insurance industry did not prepare for this event? The geologists have been warning us for years.

Jerry O'Kane: To understand the reasons, one has to appreciate the insurance mechanism. As you point out, the business of insurance is the assumption of risk. In order to do that, there are certain essential elements that must be present. One is the loss must be calculable.

As opposed to hurricanes, floods, and other natural disasters, catastrophic earthquakes are very rare and the extent of damage they are capable of producing is unpredictable.

Another requirement is the ability to distribute the risk over a large number of units. Only those people who have and appreciate their serious exposure will purchase earthquake insurance. This is known as "adverse selection." To distribute a risk of high-severity loss over a limited number of risks that have a high exposure would require a premium rate that would be unaffordable.

Frank Nutter: Well, let's get on with some of the specifics. How should policyholders go about reporting their claims and finding out whether they have coverage?

Jerry O'Kane: Well, normally people who have claims will notify their insurance agent or, in the case of direct writers, call an 800 number. But, most of the business in this community was written through local people who were equally disrupted by this earthquake. Some agents were killed, seriously injured, or had deaths or injuries in their families. Many had their businesses destroyed as well as their homes. In short, they too are victims and lack the facilities or physiological means to respond. Further, as you know, there has been serious disruption in telephone service and even now, a month later, only emergency calls are being permitted at the emergency telephone centers. Insurance companies are doing their best to open channels of communications with their policyholders, but most policyholders don't even know who their insurance companies are.

Frank Nutter: You mean that it is up to the catastrophe victims themselves to initiate contact to get any response from their insurance companies?

Jerry O'Kane: Some companies, but I suspect not all, are able to identify their risks by zip code. In other words, their computer programs are written so that they can input a zip code number and receive a printout of all policyholders in that area. But what then? If the dwelling is uninhabitable, the people will be in shelters or temporarily living elsewhere. As for the rest, should an insurer commit the critical time and substantial resources to attempt to reach each one and find out who has a claim and who does not? This would be at the expense of helping others. Instead, we are working with the American Red Cross to generate channels of communication with those who have been dislocated; and insurers are providing essential reporting information to the others through the media.

Frank Nutter: Do you have any idea how many claims will be involved?

Jerry O'Kane: It's hard to say. Some estimates run in excess of one million claims.

Frank Nutter: Does the insurance industry have enough adjusters to handle one million claims in addition to their normal claims handling throughout the rest of the country?

Jerry O'Kane: Most insurance companies have a catastrophe plan that they developed and refined over the years in responding to hurricanes, tornados, hail storms, floods, and other disasters. And, surveys have proven the insurance industry has done an outstanding job of responding to these catastrophes. But, this disaster is fifty times greater than anything we have experienced in the past. No, we don't have enough adjusters to quickly handle a million claims in addition to the other normal claims business. But, we'll do the very best we can.

Frank Nutter: We have been receiving numerous offers of help from all types of disciplines and groups. Unfortunately, we suspect some may be opportunists. The state has been diligently protecting its constituency against unscrupulous practices. Mr. Petak, what provisions have been made for licensing insurance adjusters and others who will be coming from out of state?

Dr. Petak: Well, we haven't gotten that far in our priority list yet. Clearly, we will have to get assistance in our licensing departments. Perhaps, we can consider recognizing those who are licensed in other states and issue temporary licenses.

Frank Nutter: Mr. Hayes, the Corps of Engineers has cleared most of the hallways and streets of debris and have also demolished buildings that presented a threat to public safety. What happens now?

Walt Hayes: There is a virtual mountain of debris remaining. It will take an army of people and heavy equipment to move it. Beyond that is the safe disposal of debris. We had over one hundred hazardous material spills following the quake. Another major problem is where to put it. The municipality was already struggling with the problem of garbage disposal and finding acceptable land fill sites. The ensuing fires caused enough atmospheric contamination. I'm sure the EPA would be opposed to letting us burn it. Until we can decide where to put the debris, we can't start moving it.

Frank Nutter: What happens after the debris is removed?

Walt Hayes: We have several thousand structures to inspect. Only those that obviously presented a hazard to public safety have been demolished. All the rest must be carefully inspected, decisions made as to whether they will be permitted to be repaired, and where needed, additional demolition and debris removal.

Frank Nutter: Obviously, a large number of building inspectors will be required to survey damaged buildings to determine if they can be safely occupied or if they must be torn down and removed. Unless buildings have been adequately inspected and a determination made as to their repairability, insurance adjusters will be unable to establish the amount of insurable damage and contractors will be unable to proceed. I suspect there are many registered engineers in both this state and other states. Is it not possible to arrange for engineers to assist building inspectors in the task of performing the necessary damage appraisals and assessments for the city?

Dr. Petak: You are correct in your statement that there are many registered engineers and architects in the state as well as in the country. Although there are many registered engineers, there are not many with the specific experience and knowledge necessary to perform the inspection of buildings which have experienced damage as a result of an earthquake. Further, building inspection is the responsibility of the local government, to be performed within the scope of the ordinances and regulations of the government, and cannot easily be turned over to individuals that have not been appropriately recognized as agents of the city government. In order to provide for this need, we will have to consider the possibility of deputizing qualified, registered structural engineers and/or civil engineers so that they may assist the building department. Also, it is possible that we can solicit aid from other cities and counties for assistance from their building departments. In so far as using private practice engineers, we must be sensitive to the fact that: 1) The most qualified persons in the area may be busy working with their own clients with whom they have had prior agreements. For this reason, engineers from outside the area will be needed. 2) The assessment of certain types of buildings and facilities (e.g., hospitals) require very specialized expertise.

Frank Nutter: You have all described the many problems confronting us and some of the steps that must be taken to proceed. But, my question to you, sir, is why haven't we started?

Dr. Petak: I can appreciate the strong desire, indeed the urgent need, to return all systems to normal as soon as possible. But up to this time we have been dealing with the emergency response which has included search and rescue, fire suppression, emergency food and shelter, and other coping strategies designed to prevent community systems from breaking down in the face of this disaster. Restoration, the next phase in the life of the disaster process, is characterized by efforts to complete the emergency response and move into attempts to return activities to some level of normalcy and restore some level of service to the citizens of the community. Finally, reconstruction consists of efforts to rebuild, replace, and enter into a level of activity equal to or greater than the pre-disaster condition. This will involve major reconstruction and development as well as repair of damaged facilities.

In defense of the insurance industry, it is my opinion that their responsibilities in performing damage assessment and claims adjustment cannot really be started until the emergency phase has been completed and the system begins to enter into a renewed state of normalcy. Clearly, rapid and timely claims adjustments and claims payments are critical to assisting the community in their efforts to achieve a state of normalcy. However, it is important that the industry recognize that they must work closely with the local governments involved and, in particular, with the professional engineers who have the responsibility for overall building damage assessment for the community.

Frank Nutter: Mr. O'Kane?

Jerry O'Kane: Insurers, like any competitive businesses, must operate efficiently if they are to survive. Clearly, companies cannot staff in anticipation of an event which happens only once in a hundred years. This is a new experience for our industry as well and we, like everyone else, will have to spend time going through a learning curve to get up the speed.

Dr. Petak: I might add that I hope the insurance industry would establish a priority system under which claims adjustments will be made. This might be particularly difficult for companies that write both commercial and residential business. Without careful consideration, there may be early adjustment and claims payments for properties not critical to the recovery of the community. For example, it is difficult to trade off the needs of individual homeowners against the needs of businesses. Individuals desire to replace their homes and their personal property so they may set their lives on a normal course as soon as possible. However, small businesses, many of which are marginal, may be forced to go out of business or relocate if too much time elapses between the event and their ability to reopen their operations. It is imperative, then, that the claims response segment of the insurance industry quickly establish working relationships with the building professions and work cooperatively with an overwhelmed building inspection department to make the necessary damage assessments and claims payments to those segments most critical the community's quick return to normalcy.

Jerry O'Kane: I would like to interject that cooperation is a two way street. The more existing buildings that are torn down, the longer it's going to take to return to normalcy. The insurance industry has a vested interest in the decisions to repair or raze buildings as do property owners who are uninsured or underinsured. We suspect there will be a strong tendency for the building department to quickly condemn buildings because it's easier, faster, and will be less work for them in the future. How can the insurance carriers and the property owners be protected from such hasty decisions and be assured that repairable structures are not razed and that any and all salvage value in the materials be retained by the building owner or the insurance company?

Dr. Petak: This is a difficult question to answer. The community has necessarily closed off the severely damaged areas of the city and prevented access by news media, outside engineers, insurance adjusters, and others. In the opinion of the state attorney general, the city has the authority to temporarily restrict entry into the most heavily damaged area on life-safety grounds. Also, the city officials have already authorized the demolition of a number of buildings in the damaged zone. We are aware that it has been alleged in order to remove the possibility of a few free-standing older buildings to remain in the central business district, razing has been ordered to provide a clear opportunity for redevelopment.

Frank Nutter: I sense some skirmish lines being drawn here between the interests of the municipality, the building inspectors, and property owners and their insurers. What is the best way to handle this?

Dr. Petak: It must be understood that any community will try to turn the disaster into a positive gain by achieving various kinds of improvements during the recovery process. There will efforts to accelerate development and draw into the community external capital investments to offset losses and improve the future economic status of the community. However, this by no means suggests that the disaster should be used as an opportunity to promote fast growth and development, nor does it suggest the desirability of bypassing or avoiding due process in the local community planning and development process. Property owners have the right the appeal decisions of the building departments and, if necessary, pursue their appeal through the courts. The insurance industry, in order to fulfill its contractual obligations to its policyholders can involve itself in the process.

Frank Nutter: In light of the importance of quickly restoring the community to normalcy, debating the repair/raze decisions through regulatory or judicial means would appear counterproductive.

Dr. Petak: Well, this is just another example of where planning, preparation, and accord in advance of an event would have smoothed the way for speed and efficiency. Under present circumstances and in the current environment, we can attempt to hammer out some expeditious recourse for appealing building department decisions, but it's a little late for that. In summary, it is both the insurance industry's and local government's responsibility to insure that the community returns to normalcy as rapidly as possible. Delays caused by either groups actions or a combination of actions will only result in delaying the recovery process, thus working additional hardship on both individuals and businesses. This is important so that businesses will know the sequence of their receiving both public services and payment of their insurance claims so they may proceed with restoration of their facilities and restarting of their businesses. As in the case for government officials, the insurance industry must be well organized so as to enable the community to make the most of their resources during the recovery process.

Walt Hayes: There is another area which is going to create conflict between the officials, property owners, and involve the insurance industry. This community, like most communities, didn't think that they would ever have an earthquake. None of the existing codes considered seismic safety. As an engineer, I would strongly recommend that both new construction and repairs incorporate design elements to make this city safer in the event of another quake.

Frank Nutter: Dr. Petak?

Dr. Petak: The city council as well as the state are cognizant of this need. But, as I stated before, we are just now entering the rebuilding phase. This will take some time to draft such codes, conduct public hearings, and have the codes enacted.

Walt Hayes: No architect can begin drawing plans nor can any contractor estimated costs until these codes are enacted. In fact, if the codes are going to require retrofitting, that is, will not "grandfather" existing structures, contractors will not even be able to start <u>repair</u> work, let alone reconstruction.

Frank Nutter: Who's going to pay for this?

Walt Hayes: A good question! While the typical cost to seismically engineer a building does not substantially add to the buildings costs, retrofitting existing structures can be many times the cost of repairs.

Frank Nutter: Mr. O'Kane, doesn't insurance cover this?

Jerry O'Kane: The purpose of insurance is to put things back the way they were. There's nothing in the rating structure which includes upgrading buildings to meet new code requirements. In fact, most property insurance policies specifically exclude increased costs due to building codes and ordinances.

Frank Nutter: It would seem then, that if the government decides to require a safer city, the burden will fall upon the very victims of this catastrophe.

Dr. Petak: So it seems. Unfortunately, no one anticipated this event and there is no current funding to cover it.

Walt Hayes: It has been my experience that municipalities that have experienced major catastrophes also have a tendency to take this event as an opportunity to rezone. Certainly, this will affect property owners, insurance companies, and the speed of recovery.

Frank Nutter: Let's turn our attention to insurance payments. How fast will insurance money be forthcoming?

Jerry O'Kane: Very quickly. Most insurance companies will provide advance payments to home and business owners to tide them over during the period when the damage is being measured and the adjustment process. We anticipate prompt payment in total loss situations. I should mention, however, that these insurance checks will, as we are contractually obligated to do, include the name of the mortgagees, that is, lending institutions. I'm not sure how they will be able to handle this volume.

Frank Nutter: Dr. Petak?

Dr. Petak: It will be the desire of every policyholder to have their claim paid as quickly as possible so that they may proceed with the reconstruction of their property, their businesses, and their lives. Early and/or advance payments are assumed to facilitate this process. There may, however, be some significant negative consequences of an immediate and quick response on the part of the insurance industry. Specifically, the mortgagees, that is, the banking and financial institutions, have also sustained damage and local banks are virtually unable to function. Thus, early advance payments will result in a rapid drain on limited cash resources within the financial system of the community and possibly the state. This, of course, will divert limited cash resources from other critical needs to those associated with the rebuilding process. Beyond this, the banks will want to protect their interests in the damaged property which serves as collateral for the loans and so they will not be quickly signing off on insurance checks.

Unfortunately, I don't believe the banking industry was prepared for this event either. I'm not sure how they're going to handle it now.

Frank Nutter: This is a public hearing and while I have been conducting the questioning up to this point, the governor is also very interested in questions from his constituency. I will, therefore, open this hearing to questions from the audience. You may address your questions generally or directly to one of the witnesses.

[After time limit and/or questions from audience, end]

Frank Nutter: Let's step away from our scenario now and back into our present time and place. There is a tendency to believe that earthquakes, and for that matter, other disasters, happen to other people and at other places. In fact, most people believe that earthquakes are a California problem. But that's not so, and to prevent feeding that notion, we have carefully avoided any reference to California in our scenario and made it generic. Virtually, no area of the United States is immune to earthquake and as we have seen, everyone will be impacted in one way or another when the major event occurs. Let's look at some history.

Mr. Hayes, where and how often have damaging earthquakes occurred in the past? How often will they occur in the future?

Walt Hayes: [Color slide of North America showing the location of past earthquakes during the past 25 years.]

No part of the United States is totally free from earthquakes. About 70 earthquakes large enough to be damaging (i.e., magnitudes of 5.5 to greater than 8) occur each year. Moderate earthquakes (magnitude 5.5-6.5) occur about 100 times more often than great earthquakes (magnitudes greater than 8). The frequency of occurrence is greatest in Alaska, followed by California, the Pacific northwest, Puerto Rico/Virgin Islands, Hawaii, the Western mountain states, the Mississippi Valley, the Southeast, and the Northeast. The largest past earthquakes occurred near Memphis (1811-1812), Los Angeles (1857), San Francisco (1906), and Anchorage (1964). One would expect the seismic cycle of past earthquakes to be repeated in the future represented by the next few thousand years.

Frank Nutter: What can we expect in the next 50 years in terms of occurrence and possible losses?

Walt Hayes: [Color slide of the United States showing the relative severity of ground shaking expected in the next 50 years with a 10% probability of exceedance.]

In the next 50 years, 3,500 damaging earthquakes are expected to occur. In this period, no part of the United States is free from risk from at least one of them and some parts (e.g. Alaska and California) can expect more than one. The economic losses from a single maximum-magnitude earthquake have been estimated to reach several tens of billions of dollars in California and the Mississippi Valley, several billions along the Wastach front, Utah, the Puget Sound, Washington/Portland, Oregon area, and the Southeastern United States. Loss of life and injuries, a function of the time of day, and the season of the year can potentially reach tens of thousands in the worst case scenarios.

Frank Nutter: What physical effects should be expected in a damaging earthquake of magnitude 6 and greater?

Walt Hayes: [5 slides, stating the fact and showing effects.]

The destructiveness of an earthquake depends on the magnitude and proximity of the earthquake to an urban center and the degree of earthquake risk management in place to deal with ground shaking (including aftershocks) ground failure, surface fault rupture, tsunami, and fire. These physical effects will usually not lead to devastating losses in a community if the appropriate preparedness and mitigation measures have been implemented. History, however, has shown that losses decrease as preparedness and mitigation increase. The Decade for Natural Disaster Reduction is an opportunity to do something to cut these losses.

Statistically, the probability of a magnitude 6 earthquake is 100% in the next 50 years in many parts of the United States. The probability of a magnitude 7.5 or greater earthquake in southern California is 60% in the next 30 years; it is 50% for a magnitude 7.0 earthquake in northern California.

Frank Nutter: As we witnessed from the scenario, the economic and logistical consequences of failing to plan and prepare for earthquakes are horrendous. The insurance industry is, in fact, preparing for this major event [description of The Earthquake Project].

So that's what the industry is doing. How can you, individually prepare yourself and your businesses for a major earthquake? Since we have a number of producers in the audience, I will turn that question over to Jerry O'Kane.

Jerry O'Kane: [Brief description of how agents and brokers can prepare themselves for the event.]

Frank Nutter: Are there any other questions from the audience?

The October 17, 1989 Loma Prieta, California Earthquake

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(**NOTE:** The information below represents the best available information 45 days after the earthquake.)

PREFACE

At 5:04 p.m. local time on Tuesday October 17, 1989, a magnitude (M_s) 7.1 earthquake struck northern California. The earthquake, which occurred on the San Andreas fault system, had its epicenter at 37° 2' north latitude and 121° 53' west longitude near the town of Aptos and the Loma Prieta Overlook, 70 miles southeast of San Francisco and 50 miles northeast of Monterey. The fault ruptured at a depth of 18.24 km (11 miles). Based on geodetic (geodolite and GPS) data the primary right-lateral strike slip fault did not break the surface although a complex pattern of ground cracking was found in a broad zone southwest of the surface trace of the San Andreas fault. Some of these cracks were found to be complex head scarps defining large slide masses triggered by the earthquake. The location of some of the cracks indicated a combination of intense ground shaking and rupture typically associated with the crests of ridges. The set of cracks and the broad zone of intense ground rupture at the surface are consistent with a dipping fault plane and the strain pattern expected from a major bend in the strike-slip fault in the Santa Cruz Mountains. The rupture zone, as defined by the aftershock sequence, was a 40 km (24 mile) segment from Highway 17 near Lexington Reservoir to the Pajaro Gap near Highway 101. This was the first time that an earthquake having a magnitude greater than 5.0 had occurred along the 270 mile section of the San Andreas fault that broke in 1906. The fault slip had a 1.7 m right-lateral and a 1.3 m reverse movement. Its strike was north 48° W and its dip was 70° SW.

The Loma Prieta earthquake tested the infrastructure of the San Francisco Bay region. It was a site-effects earthquake in that Bay muds amplified the ground shaking and land fill areas liquefied.

A striking feature of the earthquake was that every area experiencing liquefaction in the 1906 San Francisco earthquake liquefied again.

STRONG MOTION RECORDS

More than 90 strong motion accelerograph records in free field and building locations were recorded in the earthquake. Highlights included the following:

- o Corralitos - (strong-motion station located in Eureka Canyon) located almost on the fault, the peak horizontal ground acceleration was 0.65 g. High frequencies were greatly diminished relative to the low frequencies.

- Capitola - located near the heavily damaged section of Santa Cruz, the record had a peak horizontal ground acceleration of 0.55 g and a vertical acceleration of 0.60 g. Strong shaking lasted more than 10 seconds.

- Hollister - low frequency ground motion with peak amplitude near 0.40 g was recorded.

- San Francisco Airport and Foster City - a low-frequency signal with a peak ground acceleration of about 0.30 g was recorded.

- Oakland - peak ground acceleration of about 0.30 g was recorded.

- Nimitz Freeway area - a building located 1.8 km from the freeway experienced a peak horizontal ground acceleratiion of 0.26 g.

Buildings experienced high levels of shaking. In Watsonville at the Telephone Building, the building motion exceeded 1 g. At the Santa Clara County Building in San Jose, the building response lasted more than 100 seconds. The peak amplitude on the roof of a four-story hospital in South San Francisco was 0.70 g. The peak amplitude on the 7th level of the Palo Alto Veterans Administration Hospital was 1.09 g and 0.38 g in the basement.

The modern office buildings in downtown San Francisco withstood the earthquake ground shaking very well. This outcome was a testimony of the increasing sophistication of earthquake engineering and structural design during the past decade which has resulted in building systems capable of absorbing significant seismic energy without suffering anything more than superficial damage.

LANDSLIDES AND LIQUEFACTION

Liquefaction of sandy soils and associated ground movements caused major damage to structures and pipelines in the Marina District of San Francisco, disrupted a third of the runways at Oakland International Airport, destroyed the Highway 1 bridge at Watsonville, destroyed flood control levees along the San Lorenzo and Pajaro Rivers requiring repairs costing several million dollars.

Several thousand landslides occurred throughout the epicentral area of the Central Santa Cruz Mountains and damaged structures, blocked highways, and disrupted utilities. A landslide blocked for more than 1 month the northbound lanes of Highway 17 that links Santa Cruz and surrounding communities with the San Francisco Bay region and carries an estimated 20,000 commuters per day. Large landslides, several acres in size and with dozens of houses, moved in this earthquake damaging some houses and leaving others extremely vulnerable to damage in future earthquakes or storms.

Extensive liquefaction occurred in Santa Cruz, Watsonville, Oakland, and San Francisco.

IMPACTS

The earthquake affected 6,000,000 people. The closest towns were Santa Cruz (10 miles from the epicenter), Watsonville (11 miles from the epicenter), Los Gatos (14 miles from the epicenter), San Jose (21 miles from the epicenter), and Hollister (32 miles from the epicenter).

The initial estimates of the economic impacts, deaths, and injuries were:

- o At least $8.3 billion in direct losses (indirect losses will not be known for some time).
- o 62 confirmed deaths (as of November 29, 1989), including 41 in the Cypress Street structure collapse.
- o 3,000 injured.
- o 14,000 homeless.
- o Approximately 116,882 damaged buildings with the majority (more than 104,000) being in San Jose and Santa Clara county.

Some experts believe that insured losses will reach $4 billion, making the earthquake a "Western Hugo." Hurricane Hugo on September 17-23, 1989, caused $7 billion direct losses, with $4 billion of that total being insured loss.

COMPARISONS

The Loma Prieta earthquake brought to memory the April 18, 1906 San Francisco earthquake and the December 7, 1988 Spitak (Armenia) earthquake. The 1906 Francisco earthquake, which occurred at 5:14 a.m., had a magnitude of 8.3 and was more than 60 times more powerful than the Loma Prieta earthquake. It triggered a major fire which completed the devastation of the city, destroying 28,000 buildings. Approximately 2,500 people died and 250,000 were left homeless. The Spitak earthquake which was about one-half the size (M_s=6.8) of the Loma Prieta earthquake caused an estimated 25,000 deaths and 18,000 injuries. It left 510,000 homeless. Reconstruction costs are estimated at $16 billion. It destroyed entire communities; whereas, the damage in communities in the Loma Prieta earthquake was isolated to locations underlain by landfill.

The difference in impacts between the Loma Prieta and Spitak earthquakes is directly related to preparedness and building codes. Strict adherence to building codes in San Francisco undoubtedly saved many lives and thousands of buildings. San Francisco leadership had decided during the last 20 years to allocate resources to emergency preparedness and sound building construction. The low level of casualties in the Loma Prieta earthquake showed the benefit of the commitment to preparedness. Such a commitment was lacking in Armenia.

IMPACTS ON CITIES

Santa Cruz (population 47,000; 10 miles from epicenter)

The greatest damage in Santa Cruz was to the Pacific Garden Mall, a collection of shops in renovated turn-of-the-century buildings located in the center of town. More than 20 stores collapsed, killing 2 people. Approximately 60 percent of the downtown area was damaged or destroyed. Mobil homes slipped from their foundations. Some 120 homes in the mountains northeast of town were damaged when landslides moved. In all, 5 were killed, 862 injured, and 4.500 displaced.

Much of Santa Cruz was left without gas, electricity, and fresh water. With most of the major roadways impassable because of two collapsed bridges, damaged overpasses, rockslides, debris flows, and gaps in the pavement, Santa Cruz was virtually isolated.

A dozen fires broke out, but all were extinguished quickly. At the University of California, Santa Cruz, several thousand students camped outside until their dormitories were declared safe on Wednesday morning. Books toppled from shelves in the library, injuring several people.

Watsonville (population 23,000; 11 miles from epicenter)

Located very near the San Andreas fault system, the town sustained extensive damage to brick buildings in the town square. The Watsonville Community Hospital was closed due to damage. Power outages were reported. The St. Patrick Catholic Church, a long-time community landmark, was badly damaged.

Los Gatos (population 28,000; 14 miles from epicenter)

Two hundred fourteen people were treated for injuries, but no one was killed.

Several blocks in the Old Town district were destroyed. About 30 houses were knocked off their foundations. Several structures burned when firefighters found their efforts hampered by damaged water lines.

San Jose (population 720,000; 21 miles from epicenter)

San Jose came through the earthquake remarkably well with damage to houses and commercial and city buildings. Five hundred people were injured and five were killed. Four buildings, including one high-rise, partially collapsed. Two hospitals were without water. Inspectors found minor cracks in nearby dams. Silicon Valley computer companies were out of work on Wednesday, but resumed business on Thursday. San Jose International Airport sustained minor damages and water and gas leaks, but continued to function.

Hollister (population 12,000; 32 miles from epicenter)

Forty people were injured from flying glass. Extensive damage occurred. The roof of the J.C. Penny department store collapsed, and mobil homes were knocked off their foundations.

Palo Alto (population 55,000; 29 miles from epicenter)

Three people were killed and more than 60 were injured. Four buildings were down, including a high-rise at First and San Carlos. The Veterans Administration Hospital was evacuated and the patients were sent to Stanford

Hospital. Stanford University was closed on Wednesday due to chemical spills in its labs. Several buildings on the Stanford University campus were damaged and subsequently condemned.

Candlestick Park

Sixty-two thousand people attending the third game of the World Series were evacuated after the earthquake struck. The stadium was damaged.

Oakland (population of 725,000; 65 miles from epicenter)

The response capability of Oakland was strained to the limit to cope with the collapse of a one and one-quarter mile stretch (the Cypress Street structure) of the doubledecker Nimitz Freeway constructed in the 1950's (known also as Interstate Highway 880). When search and rescue efforts were finally completed, 41 died in the collapse. Plaster littered the city streets. The Oakland Municipal Courthouse at 7th and Washington Streets suffered major damage. At the Oakland Museum, several metal structures collapsed.

The airport reported (3,000 feet (900 m) of the runway affected by liquefaction, but it was open on Wednesday.

Numerous fires broke out, but firefighters kept them under control.

A 50-foot link span of the Oakland Bay Bridge collasped, causing at least one death. Extensive liquefaction occurred at the east toll plaza.

San Francisco (population of 720,000; 70 miles from epicenter)

The economic impacts of business disruption are unknown at this time, but are expected to be large.

The well-to-do Marina District near Fisherman's Wharf sustained extensive damage to its buildings. Forty structures were uninhabitable. Ten were killed and 200 injured. A five-alarm fire broke out. Firefighters had difficulty controlling it due to broken water lines and concern over toxic fumes. Using volunteers and flexible portable hose, a fireboat pumped water from San Francisco Bay to fight the fire, offsetting the loss of water lines. On Wednesday, an 8-block area was evacuated because of concern over gas explosions and falling debris from damaged buildings. Damaged buildings were condemned and demolished quickly.

BART was not damaged.

The Embarcadero Freeway exit was damaged and is expected to be closed to traffic for about 1 year.

More than 1,000,000 people were affected when the city's utility service was disrupted by the earthquake. Electrical power, lost immediately, was restored by 10 p.m. the same day in most of the outlying region, and within 2 to 3 days in the downtown area. Additional fires were averted by Pacific Gas and Electric Company's careful search for gas leaks before resuming electrical service. October 27, 10 days after the earthquake, there were: a) 16,000 customers in the South Bay area without gas, and b) 5,100 customers in the

Marina District without gas. One thousand of the latter group were also without electricity and water. Phone service was affected mainly by the phone "gridlock" which occurred as people throughout the Nation tried to call in.

The Transamerica Building on Montgomery Street in San Francisco produced 22 channels of acceleration data from sensors located at the foundation, basement, ground, 5th, 21st, 29th, and 49th levels. Peak horizontal accelerations were 0.10 at the foundation and 0.31 g at the 49th floor.

The south (San Francisco) abutment of the Golden Gate Bridge contained a triaxial accelerograph mounted in an office building just beneath the toll plaza. This site is 100 km northwest of the epicenter and recorded significant horizontal accelerations, 0.12 g in the north-south and 0.24 g in the east-west directions.

ISSUES

This earthquake pointed out many issues that are relevant for other parts of California as well as the Nation. They include:

- The directional characteristics of seismic wave propagation.
- Predictability of future damaging earthquakes on the San Andreas, Hayward, and Calaveras fault systems.
- Hidden damage to buildings and lifeline systems.
- The vulnerability of infrastructure in a community (i.e., its transportation, utility, and communication systems, and the critical and essential facilities that must remain functional after an earthquake) to ground shaking and ground failure.
- The safety of doubledecker (i.e, the Nimitz Freeway and the Oakland Bay Bridge) and elevated transportation systems.
- Siting structures on known landfill (i.e., mud, clay, or alluvial deposits) which can amplify the ground motion and/or undergo liquefaction (i.e., at the Nimitz Freeway and in the Marina District).
- Vulnerability of old wood frame and unreinforced masonry buildings to ground shaking (i.e, in Santa Cruz and Watsonville).
- Adequacy of community preparedness planning.
- Adequacy of emergency response during the rush hour (i.e., 5:04 p.m.).
- Adequacy of recovery planning.
- Adequacy of building standards.
- Applicability and affordability of current retrofit technologies for unreinforced masonry buildings and transportation systems.
- The degree to which economic considerations govern community decision making on earthquake preparedness, construction, and retrofit.

CONCLUSIONS

Although northern California was hit hard by the Loma Prieta earthquake, the disaster was much smaller than it might have been. The primary reasons were preparedness and building codes. The long term investments of communitites in northern California in these two types of actions during the past few decades paid off in a very small loss of life for such a devastating earthquake.

What Can Communities Do?

Decision making to avoid or to reduce losses from earthquake hazards is restricted by economic, social, and public policy factors. The principal restraint is stated by the question, "How much will it cost?" If a community decides to attempt to reduce losses from earthquake hazards, its planners and decisionmakers must face the possibility of increased costs and decide what actions are conservative and prudent.

As communities accept the premise that costs associated with specific loss-reduction actions such as avoidance, land-use zoning, engineering design, and insurance are prudent, the question that will be asked is, "How much are we willing to pay?" An initial requirement for answering this question is for the community to determine:

- o the physical causes of each natural hazard and the probability of occurrence of each hazard,
- o the current local annual loss and the potential for sudden loss from each hazard,
- o The spatial distribution and levels of relative severity expected from each hazard, and
- o the potential loss as a function of time and the implementation of loss-reduction actions.

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EXERCISES TO ILLUSTRATE SOME OF THE PROFESSIONAL JUDGMENTS MADE IN EARTHQUAKE PREPAREDNESS, WARNING AND MITIGATION

1. Senarios for hypothetical magnitude 7.6 and 8.6 events on the New Madrid Seismic Zone.

2. Identification of critical issues in preparedness planning, warning, and mitigation for selected U.S. cities.

Question 1: Scenarios have been prepared for hypothetical magnitude 7.6 and 8.6 events on the New Madrid seismic zone. The intensity maps for six cities: Memphis, Little Rock, Popular Bluff, Paducah, Carbondale, and Evansville, are provided below. For each city, use your knowledge of the soils, buildings, and lifelines exposed in each city to earthquake shaking and ground failure to:

A. Describe what will happen physically (note: refer to the glossary for the definition of intensity and to Section I for discussion of the hazard.).

B. Describe the kinds of problems that are expected during the response and recovery period in connection with:

- Management Structure
- Coordination
- Interaction
- Tasks and Procedures
- Communication
- Press
- Roads, Communications, and Critical Facilities (those that must remain functional)

C. What would be the beneficial aspects of a reliable earthquake prediction? How could it be used to reduce potential vulnerability?

D. Assuming that a damaging earthquake like the scenario event has just occurred in your State, what kinds of mitigation actions would you recommend for the reconstruction period?

STUDIES OF SIX CITIES

Maps of the six cities studied individually are shown in figures 1-6. The intensity in general in the area of a city can be determined from the map of hypothetical regional intensities, figure 7. But to zone a city in greater detail it is necessary to have some knowledge of the local geologic conitions. For this purpose, field investigations were made for each of the six cities in this study.

The assigned intensities on each city map are intended to be the maximum intensities likely--that is, those that would occur if the assumed 1811-size earthquake occurred on the part of the New Madrid seismic zone nearest that city. All of the cities would not experience these worst-case intensities at the same time. For example, if the assumed earthquake occurred near the south end of the zone, Memphis would in fact experience the IX's and X's shown in figure 7, but Evansville, which is north of the zone, and which is projected in figure 6 and figure 7 to have a maximum intensity of IX, would likely experience only intensity VIII effects. Similarly, if the earthquake were at the north end of the seismic zone, Evansville would have the IX shown, while Memphis would probably experience only intensity VIII-IX effects. However, since in the 1811-1812 series three great shocks all occurred within a short period of time (December 16, 1811 to February 7, 1812), it is possible that the cities might all experience the maximum intensities more or less contemporaneously.

The intensities shown on figures 1-6 take into account both the regional map intensity (figure 7) and the local geologic conditions at each city. The regional map gives the highest common intensity for each city, but it is the local geologic conditions that determine the actual differences in

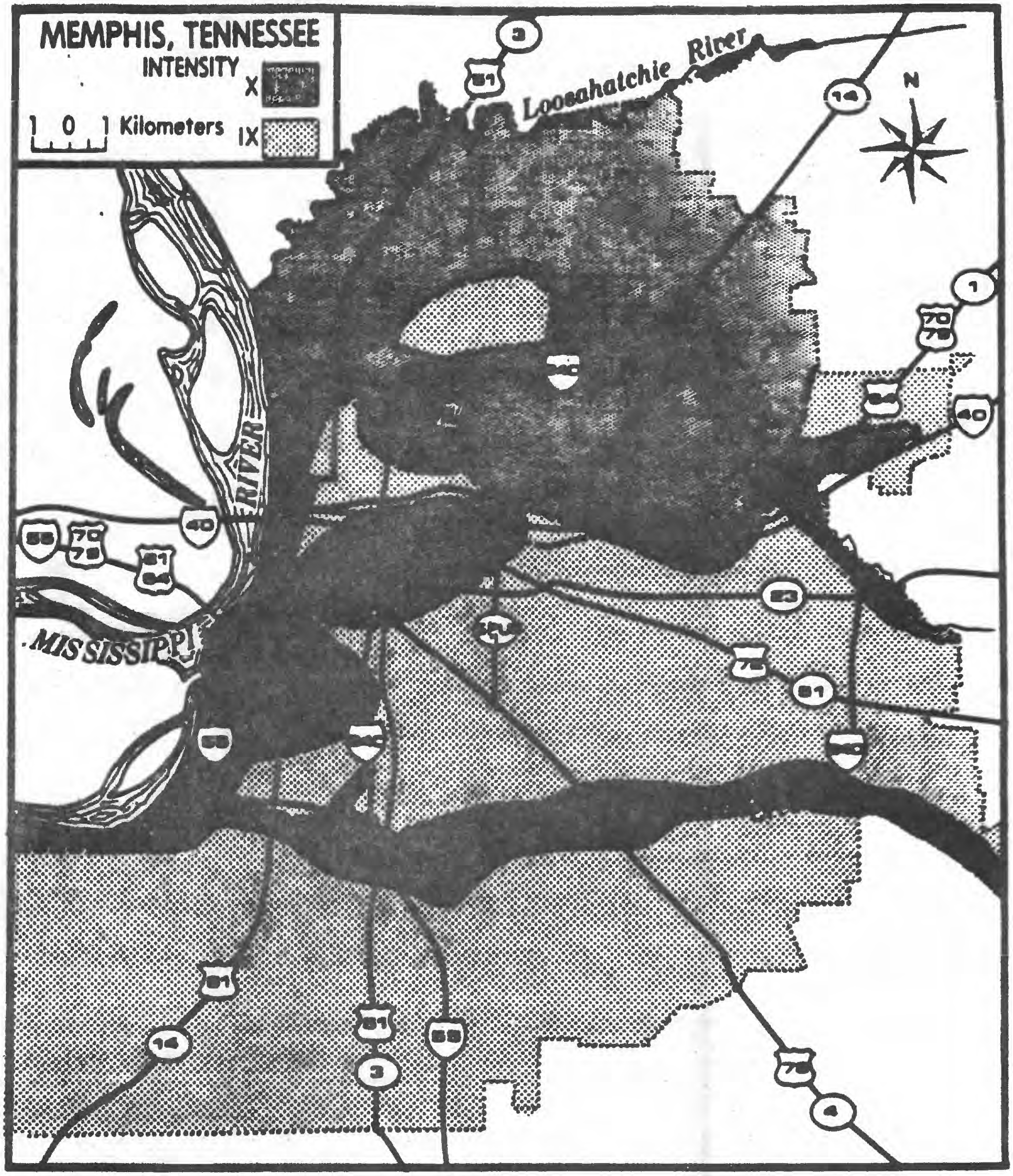

Figure 1 Hypothetical intensity map for Memphis, Tennessee. For an earthquake near the south end of the New Madrid seismic zone, intensities projected for Memphis are: X in the alluvial valleys and in the areas found by Sharma and Kovacs (1980) to have high amplification factors (figure 20) or to be susceptible to liquefaction (figure 19), and IX in the rest of the city. For an earthquake near the north end of the New Madrid seismic zone, the intensities at Memphis would be lower.

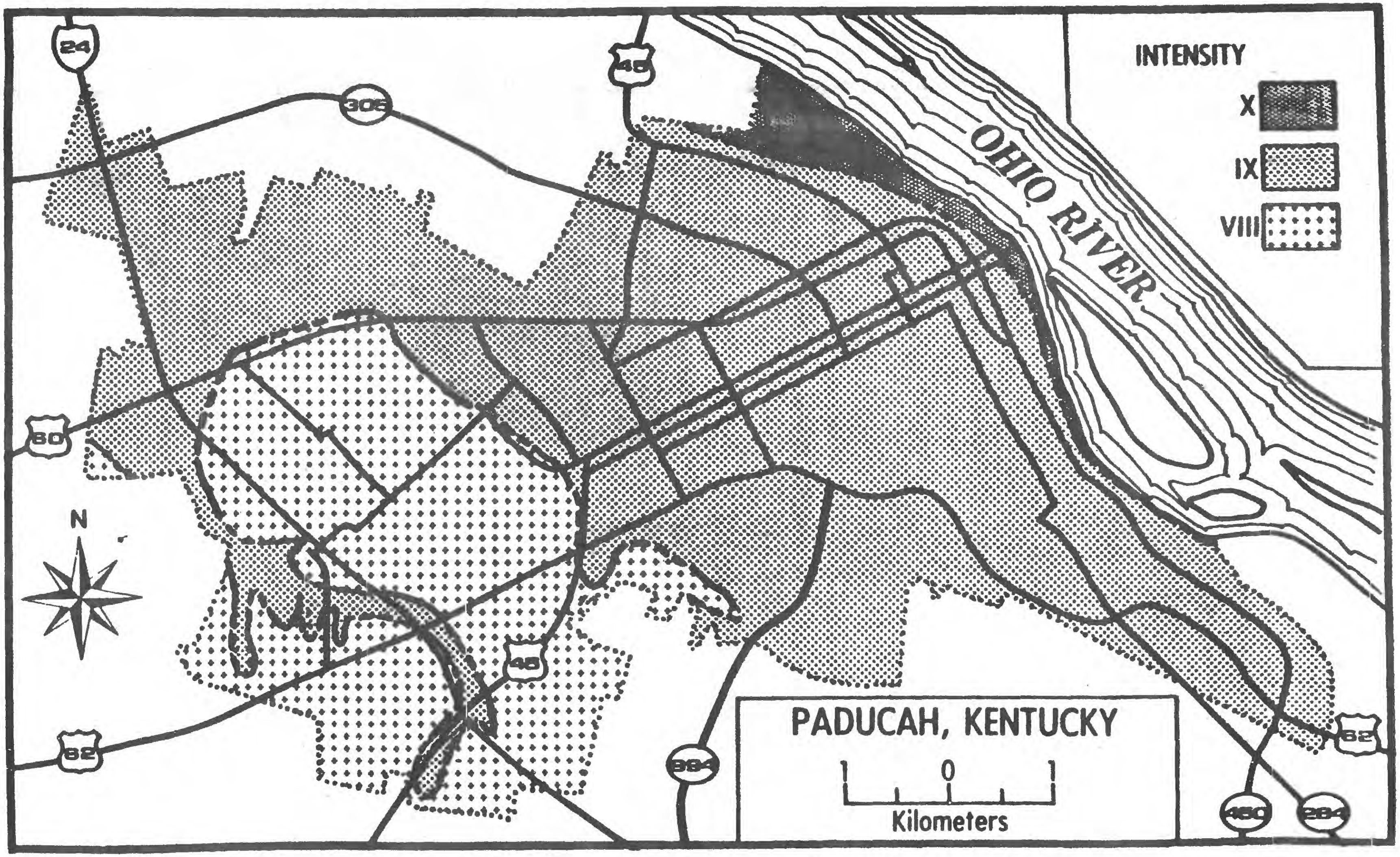

Figure 2 Hypothetical intensity map for Paducah, Kentucky. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Paducah are: X on the river alluvium, IX on the lacustrine deposits underlying most of the city, and VIII in the hills southwest of the city. For an earthquake near the south end of the New Madrid seismic zone, the intensities at Paducah would be lower.

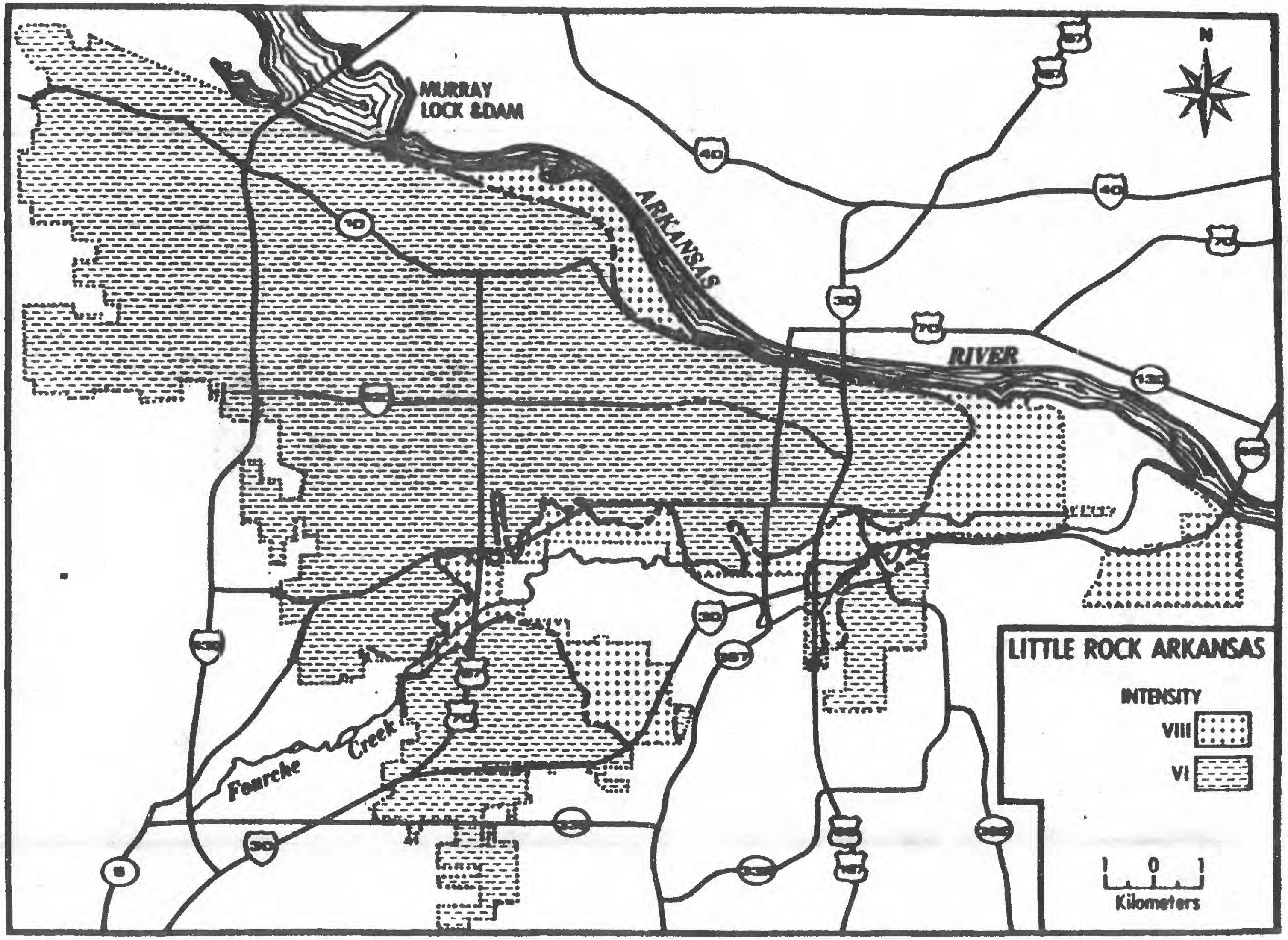

Figure 3 __Hypothetical intensity map for Little Rock, Arkansas. For an earthquake near the south end of the New Madrid seismic zone, intensities projected for Little Rock are: VIII on the river alluvium, but only VI on the sandstones, shales, and limestones of the hills. For an earthquake near the north end of the New Madrid seismic zone, the intensities at Little Rock would be lower.

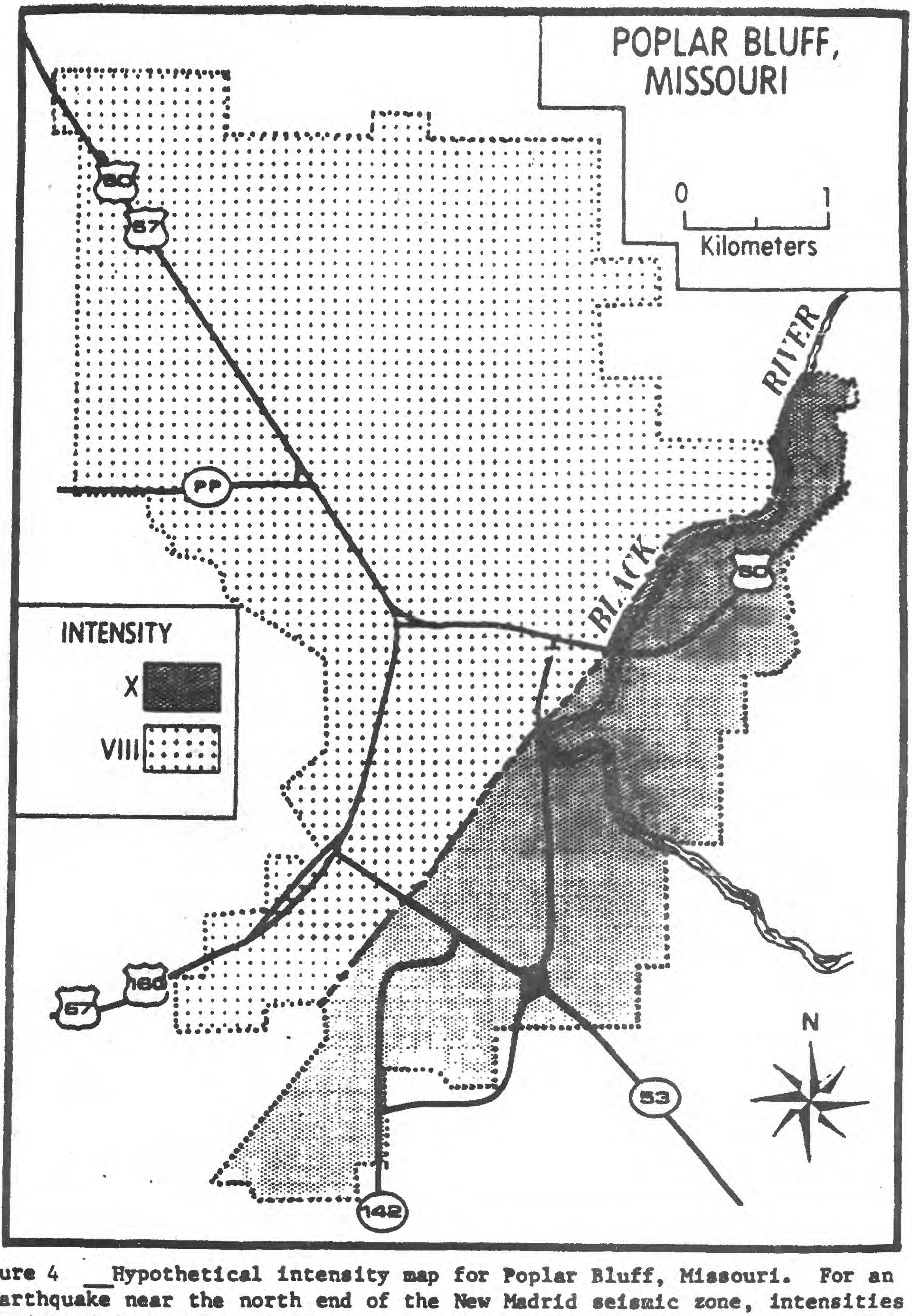

Figure 4 __Hypothetical intensity map for Poplar Bluff, Missouri. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Poplar Bluff are: X on the Mississippi flood plain southeast of the city, but only VIII on the uplands to the northwest. For an earthquake near the south end of the New Madrid seismic zone, the intensities at Poplar Bluff would be lower.

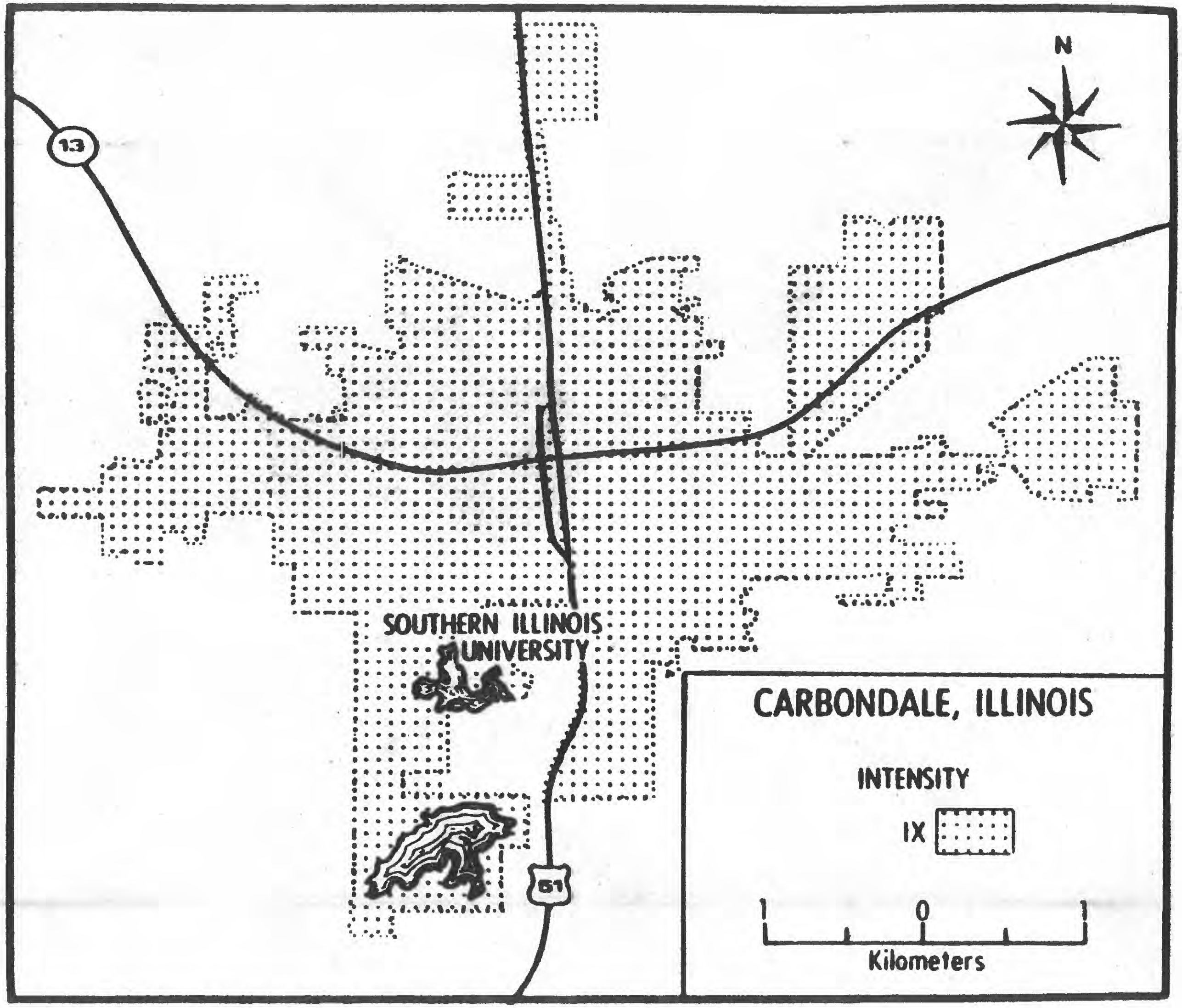

Figure 5 Hypothetical intensity map for Carbondale, Illinois. For an earthquake near the north end of the New Madrid seismic zone, the intensity for Carbondale is IX for the entire city. For an earthquake near the south end of the New Madrid seismic zone, the intensity at Carbondale would be lower.

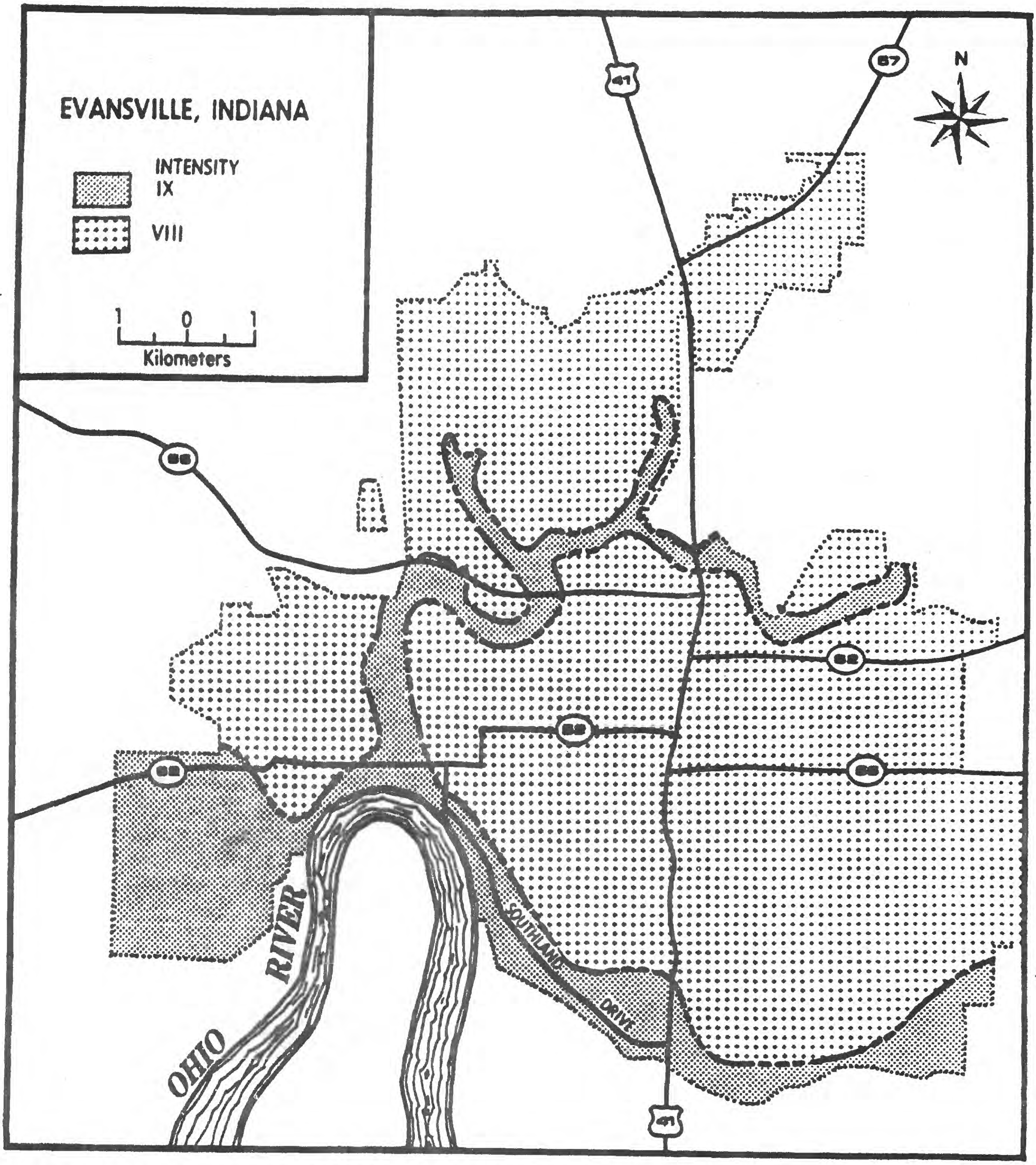

Figure 6 _Hypothetical intensity map for Evansville, Indiana. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Evansville are: IX along the Ohio River flood plain and its tributary and VIII for the lacustrine sediments of the rest of the city. For an earthquake near the south end of the New Madrid seismic zone, the intensity at Evansville would be lower.

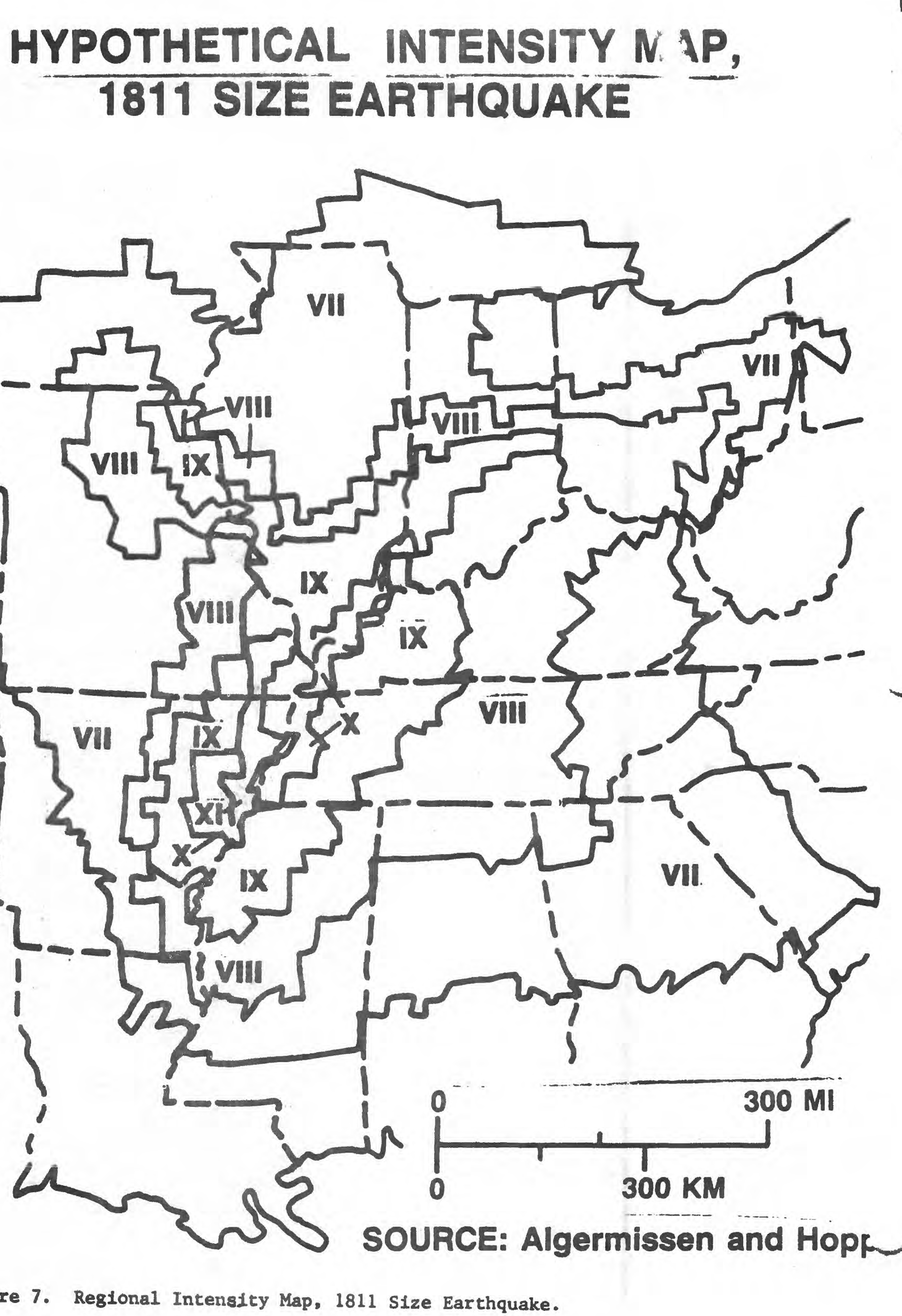

Figure 7. Regional Intensity Map, 1811 Size Earthquake.

intensities within each city. For example, one city (Carbondale, figure 5) has so little significant geologic variation as to be assigned only one intensity throughout, IX. Paducah (figure 2), on the other hand, has conditions likely to produce most severe damage along the river and sucessively lower intensities, in areas with different conditions, away from the river; the most stable locations in Paducah are thought to be two intensity levels lower than the area along the river. Thus three intensity levels are shown for Paducah. Poplar Bluff and Little Rock (figures 4 and 3) are also thought to have differences of two intensity levels, but with no intermediate-level intensity. Thus at Poplar Bluff the intensity drops abruptly at the edge of the bluff along the Black River from X in the Mississippi River alluvial plain to VIII on the uplands. Finally, geologic conditions at Evansville and Memphis suggest a difference of one intensity level.

Each of the six cities is discussed in more detail below.

Carbondale, Illinois

Physiographic description:

Carbondale is situated in the till plains of the Central Lowland province (Fenneman, 1938) in an area of very low topographic relief.

Underlying material:

The northern part of the city is underlain by lake deposits consisting of well-bedded silt and some clay; the southern part is underlain by hard, silty, sandy, and clayey till with some sand and gravel (Lineback, 1974). These deposits are probably at least 50 feet (15 m) thick and overlie interbedded sandstone, shale, limestone and coal of Pennsylvanian age (Williams and others, 1967).

Physical property tests and other information:

Selected standard penetration tests (18 inch drop of a 40-lb hammer) show N values that range from 9 blows/foot near the surface to 40 at depths of 50 feet (15 m) (Pulley, Gary, Assistant Soils Engineer, Illinois Department of Transportation, Carbondale, Illinois, oral communication, September 15, 1982). (In shallow alluvium N values are generally about 10; in denser materials N values are higher. Liquefaction potential is highest at low N values.)

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. Landslides in response to strong earthquakes are unlikely.

2) Liquefaction. The liquefaction potential is low.

Hypothetical intensity map for Carbondale:

The highest projected intensity at Carbondale is IX M.M. from the regional map (figure 7). This intensity would occur for an 1811-size earthquake anywhere near the north end of the New Madrid seismic zone. Carbondale would experience only intensity VIII for an 1811-size earthquake near the south end of the seismic zone. The 1895 epicenter (on which the hypothetical intensities are based) is only 81 km from Carbondale (see table 4 and Appendix 2), accounting for the high intensity projected there; there is no information about what happened in Carbondale in 1895. Although the 1968 earthquake is closer (69 km) to Carbondale, and overturned oil tanks in Carbondale (Coffman and Cloud, 1970), it is not in the New Madrid seismic zone, and an earthquake of the size studied in this report is not deemed likely at the 1968 epicenter.

The seismic zonation of Carbondale is based primarily on the site geologic conditions. Although different geologic units can be differentiated at the surface, they are not deemed significantly different with respect to intensity values. Nor are landslides or liquefaction effects particularly likely at Carbondale. Thus the map of Carbondale shows only one M.M. intensity value, IX. Again note that this is the highest projected intensity, and that every building in Carbondale is not expected to be damaged at the intensity-IX level. Some buildings may not be damaged at all. Rather, the predominant part of the most important damage will be at this level.

Evansville, Indiana

Physiographic description:

Evansville is situated along the Ohio River in the Interior Low Plateaus province (Fenneman, 1938). Topographic relief within the city proper is low; some of the banks along the Ohio River are steep.

Underlying material:

Much of the city is underlain by lake deposits consisting of clay, silt, and sand that are Pleistocene in age (Gray and others, 1970); Recent alluvium occurs along the flood plain of the Ohio River; thickness of these materials was not given in the data reviewed, but is inferred to be in the tens of feet rather than in the hundreds of feet. Beneath these surficial materials are well indurated shale, sandstone, limestone and some coal belonging to the McLeansboro Group of Pennsylvanian age.

Physical property tests and other information:

Specific test data were not available as of this writing. However, test data is available in the files of private consulting firms. According to Richard Eifler, City Engineer, landslides are not a problem throughout most of the city; however, along the river bluff near Reitz School oversteepening of a side hill cut during railroad and highway construction caused a landslide.

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. A strong earthquake probably would not cause landslides throughout most of the city; however, landslides probably would occur along the steeper bluffs adjacent to the Ohio River. Some compaction and differential settlement of flood plain alluvium probably would also occur.

2) Liquefaction. While a liquefaction potential exists throughout much of the city, it is low and would be localized; the liquefaction potential in the alluvium along the Ohio River flood plain is probably high.

Hypothetical intensity map for Evansville:

Intensities projected at Evansville are VIII and IX M.M., for an earthquake near the north end of the New Madrid seismic zone (figure 7). An earthquake near the south end of the seismic zone would produce only VII and VIII at Evansville. Evansville is approximately 200-400 km away from earthquakes located along the New Madrid seismic zone (table 4 and Appendix 3), and there are no reports for Evansville from any of the larger earthquakes in the zone, except that the 1895 earthquake was felt. Also, there was slight damage (VI) from the nearby (81 km) 1968 earthquake north of the New Madrid seismic zone.

The higher of the two projected intensities at Evansville follows the alluvium of the Ohio River flood plain and its tributary. In this area liquefaction is a strong possibility in the event of an earthquake along the northern end of the New Madrid seismic zone. Also in this area, landslides might occur along the bluffs overlooking the Ohio River. The potential for liquefaction and landslides, as well as for vibration damage, is less on the lake sediments of the rest of the city, the area shown on figure 11 as VIII.

Little Rock, Arkansas

Physiographic description:

Little Rock is situated on the border between the Ouachita province and the Mississippi Alluvial Plain (Fenneman, 1938). Most of the city is located south of the Arkansas River, west of the Mississippi Alluvial Plain, and north of Fourche Creek in the subdued Ouachita Mountains. Within the city area these mountains have a maximum total difference in topographic relief of about 150 feet (46 m) above the Arkansas River. By comparison the Mississippi Alluvial Plain and the Arkansas River flood plain exhibit little topographic relief.

Underlying material:

Most of the city is underlain by the Jackfork Sandstone of Pennsylvanian age (Haley and others, 1976); some shale is interbedded with the sandstone and a fairly thick shale bed is present at the base of the bluff along the Arkansas River near the Murry Lock and Dam. These rocks have been intricately thrust faulted; the faults are inactive; most of them trend east-southeast and the attitudes of the beds vary over short distances.

A part of the city north of Fourche Creek is underlain by Tertiary age interbedded sand, calcareous clay, limestone, silty clay, and silt of the Midway and Wilcox Groups (Haley and others, 1976, and Gordon and others, 1958); these materials are here about 65 feet (20 m) thick.

Along the Arkansas River and where it passes into the Mississippi alluvial plain the underlying material generally consists of dense silty sand, sand, silty clay, and gravel.

Residual soils developed on the Jackfork Sandstone are a gravelly silt loam, shallow to fairly deep, and moderately permeable; soils developed on the Wilcox and Midway Groups are a silty to sandy loam, shallow to fairly deep, and slowly to moderately permeable (Haley, Bickner, and Festervand, 1975, and Soil Conservation Service, 1967).

Physical property tests and other information:

Well logs of three test hole borings were provided by Mr. Jake Clements, Engineer with the Materials and Tests Division, Arkansas Highway Department, Little Rock. Two logs at the Arkansas River crossing of I-440 indicate that the material consists mainly of silty sand in the upper 20 to 30 feet (6 to 9 m) and sand and gravel below that to the depths of the holes, which terminated at 62 feet (18.9 m) and 110 feet (33.5 m); the material is non-plastic, and N values for standard penetration tests range from about 10 in the upper part to 32 and 52 in the lower parts. The log in alluvium along Fourche Creek east of the intersection with U.S. highway 65 consists mainly of silty clay, and sand and gravel near the bottom of the hole at a depth of 55-60 feet (17-18 m); N values are variable; they range from 5 to 10 in the upper part and 41 in the lower 5 feet (1.5 m) of the test section.

According to Mr. William Bush, Geologist, Arkansas Geological Commission, landslides are a minor problem in the vicinity of Little Rock. A landslide occurred at the south end of High Street north of the Chicago, Rock Island and Pacific railroad tracks; it was caused by oversteepening of an artificial cut (Michael Batie, City Engineer, Little Rock, oral communication, 1982). There is also evidence of sloughing and minor landsliding in the bluff along the Arkansas River near the Murry Lock and Dam.

Geologic mapping in the vicinity of Little Rock has not revealed any surficial features that could be attributed to liquefaction (Boyd Haley and William Bush, oral communication, 1982).

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. Landslides in response to strong earthquake vibrations are unlikely throughout most of the city. However, sloughing and small landslides could occur along some of the steeper bluffs.

2) Liquefaction. The liquefaction potential is very low for the part of the city underlain by the Jackfork Sandstone and by units of the Midway and Wilcox Groups. The liquefaction potential is probably low to moderate for the part of the city underlain by flood plain deposits of the Arkansas River and the Mississippi Alluvial Plain.

Hypothetical intensity map for Little Rock:

Intensity VII M.M. is projected at Little Rock on the regional map (Figure 7) for an epicenter near the south end of the New Madrid seismic zone. Little Rock is 170-360 km away from earthquakes in the New Madrid seismic zone, and experienced intensities of IV, V, and I-IV in 1843, 1895, and 1968 (table 4 and Appendix 4).

At Little Rock the hypothetical intensities change from VIII for river and stream alluvium to VI for the neighboring sandstone, shale, and limestone hills of the rest of the city. Landslides are unlikely for most of the city, but a few small landslides might occur along some of the steeper bluffs. There is a moderate potential for liquefaction in the flood plain deposits (area shown as VIII in figure 3), although no geologic evidence of previous liquefaction in the area has been found.

Memphis, Tennessee

Physiographic description:

Memphis is situated in the Coastal Plain Province along the border between the East Gulf Coastal Plain and the Mississippi Alluvial Plain. The locally steep bluffs adjacent to the Mississippi River along the west edge of the city are 60 to 100 feet (18 to 30 m) high. Most of the city is located south of Wolf River and north of Nonconnah Creek, an area of low topographic relief.

Underlying material:

A generalized description of the underlying materials in Memphis and vicinity is given in table 6 and an east-west geologic cross section through Memphis in figure 17. Both are from M & H Engineering and Memphis State University (1974).

TABLE 6.__STRATIGRAPHIC SECTION. SECTION AT MEMPHIS, TENNESSEE, FROM M & H ENGINEERING AND MEMPHIS STATE UNIVERSITY (1974).

Series	Subdivision	Range of Thickness - meters	Description
Holocene	Redeposited Loess	0-10	Generally water-logged silts or silty clays with a 1-2m. crust in dry weather.
	Alluvial sands and gravels	0-6	Gray, fine to medium sands with occasional gravel, low to medium relative density.
Pleistocene	Loess	0-16	Wind-deposited clayey silts and silty clays.
	Sandy clay	0-3	Very stiff silty clay, possibly old erosional surface.
	Terrace sand	0-60	Fluviatile medium grained and gravels sands and gravels, very dense, generally brown or red frequently iron-oxide -cemented.
Eocene	Jackson(?) Group	0-150	Hard, fat clays interbedded toward east and south with fine, very dense white sands.

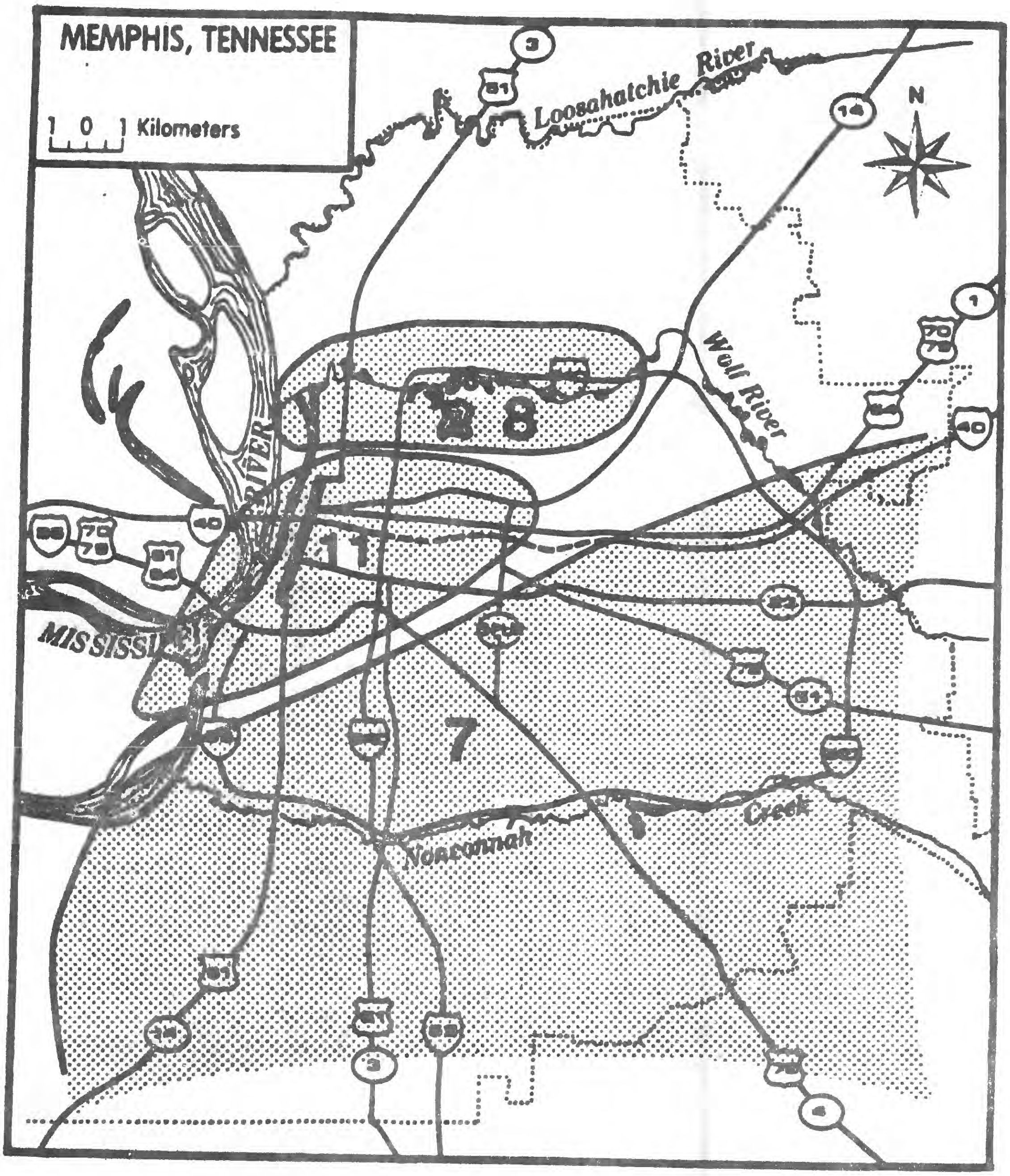

Figure 8.__Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Figures within shaded areas indicate the number of sites investigated for Sharma and Kovacs' study within each shaded area.

Physical property tests and other information:

The general locations for boreholes from which Sharma and Kovacs (1980) collected data are shown in figure 18. To protect confidentiality of the sources, exact locations of bore holes are omitted. By calculating relative density and shear strength from standard penetration resistance and using other factors, Sharma and Kovacs concluded that there are three zones likely to be susceptible to liquefaction (see figure 19).

Terzaghi (1931) describes a landslide that occurred at Memphis in 1926 and attributes the failure to movement of ground water. Mr. Richard Hoffman, Acting City Engineer, City of Memphis, said that during the last several years there have been no significant problems with landslides, but that they had minor problems with differential settlement along parts of Riverside Drive where it is located on an old fill that was not placed according to present day engineering practice (oral communication, 1982).

Fuller (1912) describes landslides along Chickasaw Bluff, 50 to 100 miles (80 to 160 km) north of Memphis along the east side of the Mississippi River (see figure 3) that could be classified as horizontal block glides, and implies that they were caused by the earthquake sequence of 1811-1812. Information useful in reaching a conclusion about the possibility of the occurrence of horizontal block glide landslides is meager and inconclusive.

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. Depending upon ground water conditions, smaller landslides will probably occur along the Mississippi River bluffs in response to strong earthquake vibrations, and differential compaction will take place over many areas of artificial fill. The occurrence of horizontal block glide landslides cannot be ruled out entirely.

2) **Liquefaction.** Areas of potential liquefaction within the city of Memphis are shown in figure 19, (from Sharma and Kovacs, 1980). The liquefaction potential is probably high for the area underlain by Mississippi River flood plain deposits.

Hypothetical intensity map for Memphis:

The highest projected intensities at Memphis are IX-X M.M. from the regional map (figure 16). These intensities would occur in the event of the assumed 1811-size earthquake at the south end of the New Madrid seismic zone. If the assumed earthquake occurred at the north end of the seismic zone, intensities at Memphis would range from VIII to IX. However, the worst case assumes an earthquake at the 1843 epicenter (on which the southern part of the hypothetical map is based), just 32 km away (table 4 and Appendix 5). That earthquake produced fallen chimneys and cracked brick walls at Memphis, and hundreds of people ran into the streets. The much larger 1811 earthquake, 80 km from Memphis, resulted in a IX at Fort Pickering near Memphis.

Zonation of intensities in Memphis takes into account three kinds of data: 1) local geologic conditions, 2) amplification of seismic waves over bedrock ground motion, as defined by Sharma and Kovacs (1980), and 3) areas potentially susceptible to liquefaction, also from Sharma and Kovacs (1980).

The alluvial valleys of the Mississippi, Loosahatchie, and Wolf Rivers and Nonconnah Creek are thought to represent slightly more hazardous geologic conditions than the rest of the city. All have upper alluvial strata resting on loose, fine-to-medium grained sands, which could liquefy at intensity IX or greater (M & H Engineering and Memphis State University, 1974). Also, areas of artificial fill, especially old, poorly engineered fill, are somewhat more likely to have damage. Finally, the bluffs along the Mississippi River are susceptible to landslides in the event of the large, nearby earthquake assumed for this study. A particularly critical area for landslides is the east bank of the Mississippi River from about I-55 to about I-40 (figure 13) (M & H Engineering and Memphis State University). This was the site of the 1926 landslide.

Sharma and Kovacs (1980) developed synthetic accelerograms for a potential earthquake of magnitude $m_b = 7.0$ located at 50, 100, and 200 km from Memphis. They found that attenuation for their 50-km-away shock would produce at Memphis intensity IX, a bedrock acceleration of 18% g, a predominant period of about 0.35 seconds, and a duration above 5% g of about 19 seconds. Using borehole data (proprietary) and local sources of information (figure 18), they computed selective amplification factors for various parts of Memphis (figure 20). They found higher amplifications in assumed looser materials close to the Mississippi and Wolf rivers; pockets of stiff clays showed very small amplifications. They suggest that the amplification diminishes toward the southeast because of a lower water table and denser soils away from the rivers. Their maps for the earthquakes at 100 and 200 km are similar to figure 20, but the 200-km map shows somewhat higher amplification toward the southeast. Although their 200-km-away earthquake only produces bedrock accelerations of 11% g and intensities of VII-VIII at Memphis, it has a predominant period of 0.67 seconds and a duration above 5% g of 25 seconds. Sharma and Kovacs therefore suggest that the higher amplifications for the 200-km-away earthquake are due to its longer duration and to its longer period content which is in the 0.7 to 1.0 second range of the natural period of the soils. They also point out that an even more distant earthquake, having a predominant period of 1 second at Memphis, would cause even greater amplifications, but because of the attenuation of acceleration with distance, the surface accelerations would be comparable to their design earthquakes. Moreover, because of the predominant periods generated, they conclude that the 50-km-away earthquake is likely to be more damaging to structures of 3-4 stories, while the 100-and 200-km-away earthquakes will be more hazardous to 9-10-story structures.

Structural damage may occur not only from the strength of the vibrations, but also because of loss of the bearing capacity due to liquefaction. Sharma and Kovacs (1980) also investigated the liquefaction potential of several of the layers from data available for Memphis. Their findings are shown in figure 19, and the number of boreholes from which they obtained their input data in figure 18. They assumed that sands with a relative density greater than 75% would not liquefy for a sufficient time period to initiate loss of bearing capacity.

All three of these factors (geology, amplification, liquefaction) were considered in the development of the Memphis map, figure 13. The slightly higher intensity on the alluvium can be seen in the areas of X along the Mississippi, Loosahatchie, and Wolf Rivers and Nonconnah Creek. Some of these areas correspond to the areas of high amplification (shown in figure 20) on the north and west sides of the city. Two of the three areas of potential liquefaction (shown in figure 19) are also included in the high amplification areas, but the central one from figure 19 can be distinguished as a separate area of potential X in figure 13. In addition, there are areas throughout the city on old, poorly engineered, artificial fill, where differential settlement may occur. Finally, landslides are likely along the Mississippi River bluffs.

Paducah, Kentucky

Physiographic description:

Paducah is situated in the upper part of the Mississippi Embayment that is also called the East Gulf Coastal Plain (Fenneman, 1938) and near the confluence of the Tennessee and Ohio Rivers. Topographic relief is low for most of the city; total difference between the Ohio River and outlying suburbs is about 150 feet (46 m).

Underlying material:

Most of the city proper is underlain by a Pleistocene and Recent sequence consisting of silt, clay, and some sand.

Physical property tests and other information:

Standard penetration tests were not available at the time of this writing. However, other tests indicate that the material has the following engineering characteristics (Nichols, 1968): 1) percolation is slow to moderate, 2) generally the moisture content is high, 3) cut slopes will stand in 20-foot (6-m) high, nearly vertical slopes when dry, but decrease greatly with increase of moisture content, 4) compressive strength is moderate when dry, but decreases rapidly as moisture content increases, 5) easily moved with hand or power equipment in most places, 6) erodes rapidly, and 7) susceptible to frost heave.

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. On slopes where soil-moisture content is high, landslides should be expected in response to strong earthquake ground motion (Nichols, 1968).

2) Liquefaction. Much of the ground underlying Paducah would be susceptible to compaction, high amplitude ground motion, and possible liquefaction in response to strong earthquake shaking (Nichols, 1968).

Hypothetical intensity map at Paducah:

The highest projected intensities at Paducah are VIII-X M.M. from the regional map (figure 7). This range of intensities would occur for an 1811-size earthquake near the northern end of the New Madrid seismic zone. The range would be somewhat lower for an epicenter farther south. Paducah is only 81 km away from the epicenter of the 1895 earthquake and experienced an intensity of VIII during that shock; a number of chimneys fell and several walls were cracked (table 4 and Appendix 6). Also, a few bricks fell from chimneys, resulting in intensity VI in 1968.

Intensities projected at Paducah decrease from the X in the alluvium along the river to IX in the lacustrine deposits on which most of the city is situated, to VIII in the hills in the southwest part of the city. Landslides are possible on slopes with high moisture content, and liquefaction is a possibility, especially along the river in the area shown as intensity X.

Poplar Bluff, Missouri

Physiographic description:

Poplar Bluff is situated on the border between the Ozark Plateaus and the Mississippi Alluvial Plain (Fenneman, 1938). Most of the city is located on the mildly dissected uplands of the Ozark Plateaus west of the Black River; a small part of the city occupies the flat Mississippi Alluvial Plain east of Black River.

Underlying materials:

The surface is underlain by sandstone, chert, and interbedded fine-grained dolomite which comprises the Roubidoux Formation of Ordovician age (McCracken, 1961). Deep residual weathering of these materials has produced the surficial soils on which most of the city is constructed. The soils are somewhat compact, medium stiff, dense, and consist of silty clay, sand and some gravel. East of Black River the underlying materials are typical river alluvium, sand, silt, gravel and clay.

Physical property tests and other information:

A test bore hole at the Veterans Administration Hospital is typical of several others located in the city west of Black River (Smith, Sam, City Engineer and head of the Sam Smith Engineering Consulting firm, Poplar Bluff, Missouri, oral communication, September, 1982). The test hole penetrated residual soils to a depth of 57 feet (17 m) where a cherty dolomite was encountered; the residual soils consist of silt, clay, sand and gravel. N values for standard penetration gradually increase from 12 at 38 feet (11.6 m) to 78 at 54 feet (16.5 m).

Test hole data in the alluvium west of Black River was not observed. However, the silty sands and clays in the alluvium have low plasticity, and at one bridge location the material consists of a clean sand at a depth of 20 feet (6 m) (Malloy, Dan, Engineer of Soils and Geology, member of the Sam Smith Engineering Consulting firm, Poplar Bluff, Missouri, oral communication, September, 1982). Also, bridge pile driving caused heaving in adjacent sidewalks.

Potential for landslides, liquefaction, and other geologic effects:

1) Landslides. In response to strong seismic shock small landslides would probably occur locally along the steep bluff just west of Black River and in steep artificial slopes.

2) Liquefaction. The liquefaction potential is probably low in the part of the city west of Black River. East of Black River the liquefaction potential is high.

Hypothetical intensity map for Poplar Bluff:

From the regional map (figure 7) intensity IX is projected at Poplar Bluff. Much higher intensities (IX and X) are projected in the Mississippi flood plain southeast of the town than on the uplands to the west and northwest (VII-IX). The difference is judged to be at least two intensity levels at Poplar Bluff, with X below in the river alluvium and VIII above on the uplands. The projected intensity values are so high because of the assumption of an epicenter at the north end of the New Madrid seismic zone. The epicenter of the 1895 earthquake, which domintates the northern part of the regional map (figure 7), is only 94 km from Poplar Bluff (table 4 and Appendix 7), and the presumed epicenter of the February, 1812, earthquake only about 80 km away. There is no information on the 1812 effects at Poplar Bluff, but the 1895 earthquake was felt there, causing a noise like a cyclone. Also, the 1968 earthquake resulted in intensity V at Poplar Bluff.

Question 2: Critical Issues in preparedness planning, warning, and mitigation.

Using panoramic views of selected cities, identify the critical issues in each city that must be confronted with regard to:

A. Preparedness planning, including response and recovery.

B. Warning (technical and societal components).

C. Mitigation (building codes, land use, non-structural, mitigation, PEPPER, etc.).

Cleveland:

The largest city in the State of Ohio is Cleveland which is located on the south side of Lake Erie. It is one of the major ports in the Great Lakes area enriched by large container facilities, and has a 1988 population of about 547,000. It is noted for several major medical research centers in the area which have been responsible for many recent advances in the health sciences and have introduced significant opportunities for employment. Cleveland is also known for its richness in ethnic neighborhoods which have brought great diversity to the city. Recent urban redevelopment programs which started in the early 1970's have revitalized the central downtown core which for many years had been consumed by blight and obsolescence. Cleveland's skyline is punctured by the lofty towers of office buildings and financial service structures from which express freeways and new developments fan out in all directions from the lake front. Sports activities are a major force in Cleveland, which is well known for its home teams: Cleveland Browns (football), Cleveland Cavaliers (basketball), and Cleveland Indians (baseball).

Nashville:

Nashville is the capital city in the State of Tennessee located on the Cumberland River as it flows westward toward the Tennessee River. It is the second largest city in the state with a population of 462,000. Located in the center of Tennessee, major expressways fan out from the inner city in all directions of the compass to reach new developments in the surrounding suburbs. As the state's capital city, Nashville is one of the more important financial and government offices service centers in the state. In recent years many new high-rise building complexes have been added and embellished by extensive terraced gardens as an extension to the old downtown area

St. Louis:

"Gateway to the West", St. Louis is located near the confluence of the Mississippi and Missouri Rivers. Founded in 1764 by French fur traders, it now spreads for 19 miles along the western shore on the Missouri side of the Mississippi River with a population of 453,000 across from East St. Louis on the opposite shore in Illinois. It is the busiest inland port on the Mississippi as well as a major railroad and highway hub. Transportation is its number one business. Over the years the central downtown core has undergone several phases of substantial redevelopment, one area in which, along the shores of the river, is located the immense Gateway Arch sheathed in stainless steel. The revitalized downtown area consists of towering office buildings, historic structures of architectural importance and prominence, major shopping centers, numerous hotels and large apartment complexes.

Indianapolis:

Well known throughout the world as the home of the annual 500-mile "Indianapolis Speedway" auto race, "The Indy", the city is the state capital and largest urban center in the State of Indiana with a population of 710,000. Located in almost the exact center of the state, the city has had the freedom to spread-out in all directions of the compass. In terms of urban planning, its growth and development has abstractly followed the doughnut shape with a central business and financial core in the center and detached dwelling residential subdivisions and suburban communities radiating out from there. It represents a classic example of the deterioration of the inner central core of a city as surrounding areas are developed with regional shopping malls, new housing and schools, and less congested subdivisions. During the late 1970's a massive redevelopment program was instituted in which the city's center was completely rehabilitated by the construction of new high-rise office complexes, government office buildings, well landscaped open spaces, parks, and improved traffic circulation. During this period many historic buildings, such as the main central railroad station, were carefully restored and remade an integral part of the city. The topography of the city is relatively flat with the White River which cuts across the city eventually flowing into the Wabash River at south-west corner of the state.

Knoxville:

As the third largest city in the State of Tennessee, Knoxville has a 1988 population of 174,000. Located in the east side of the state, it is found in a dynamic environment which makes-up part of the eastern Overthrust Belt. Knoxville straddles the headwaters of the Tennessee River which is spanned by three major bridges. Its topography is fairly complex as the city is wedged between the Cumberland Plateau, including the Pine Mountains and the Cumberland Mountain range, toward the north-west and the Great Smoky Mountains toward the south-east with the Tennessee River Valley in the middle. Knoxville is the home of TVA and a neighbor to the Oak Ridge Laboratory. There are approximately 450 traditional and high-tech manufacturers operating in the Knoxville area. The urban fabric of the city features low density, medium-rise building characteristics in a territory heavily interspersed with natural vegetation and openly landscaped areas.

Memphis:

Located in Tennessee, Memphis is the largest city in the state with a population of 648,000. It is in the south-west corner of the state along the Mississippi River which also forms the state line with Arkansas to the west where two major steel bridges cross the river. Memphis is the old cotton capital on the Mississippi founded by Andrew Jackson and others in 1819. More than one-third of the total U.S. cotton crop still passes through the Cotton Exchange situated in Memphis. Memphis is a center for barge traffic along the Mississippi and stern-wheel boats still preserve its riverside heritage. In the U.S., it is also renown for the Elvis Presley estate "Graceland", one of the greatest tourist attraction located in the city. Many historic districts are found in the city which maintains its southern legacy. In recent years the central commercial and financial areas in the downtown part of the city have seen a renaissance in the reconstruction of new multistory structures and historic parks, however the extended region is still predominantly saturated with an older, existing infrastructure which does not have the potential performance

HOMEWORK

For your State and community, answer the following questions:

A. Have local jurisdictions adopted the seismic design provisions of a building code? Which one?

B. What design criteria were used for high occupancy buildings that are typically subject to a building code? Name some important buildings in your community.

C. What design criteria was used for critical facilities (those that must remain functional after an earthquake)? Name some of these facilities in your community and State.

COURSE 3

SITING, DESIGN, AND CONSTRUCTION

A READER ON EARTHQUAKE HAZARD REDUCTION IN THE CENTRAL UNITED STATES

CONTENTS

SITING, DESIGN, AND CONSTRUCTION

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ABSTRACT

Past earthquakes have taught professions the following important lessons concerning siting, design, and construction practices:

Siting

- Earthquakes tend to recur where they have occurred in the past as a function of the seismic cycle of faults and seismogenic structure.

- The physical parameters of the fault zone or seismogenic structure (e.g., length, width, rupture mechanics, fault type) and changes in thickness, physical properties, and geometry of the soil rock column underlying the building site control the main features of the amplitude, spectral composition, and duration of ground shaking.

- A long fault (32 km or more) is required in most parts of the world to generate a large or great earthquake (magnitude 7 or greater).

- When the natural periods of vibration of soil column and the building are closely matched, the potential for damage is greater, especially at distant locations from the epicenter.

Design

The primary causes of damage to buildings are almost always a result of one or more of the following factors:

- Underestimation of the amplitude, spectral composition, and duration of ground shaking.

- Underestimation of the geotechnical properties of the foundation materials with respect to their potential for liquefaction, differential settlement, and landslides.

- Omissions in engineering analyses (for example, neglect of torsion, overturning effects, static equilibrium of forces, etc.).

Construction

The primary causes of damage to buildings are directly related to:

- Use of lateral-force-resisting-systems that are not seismically resistant (for example, unreinforced masonry, brittle concrete columns, etc.).
- Lack of adequate connections and detailing.
- Poor quality of construction.

Earthquake-Resistant Buildings

Earthquake-resistant buildings have a lateral-force-resisting system that is:

- Continuous (forces are transferred from their point of application to their point of resistance without discontinuities).
- Ductile (construction materials are stable when strained beyong their yeild limmits).
- Complete (no missing links, inadequate joints, or brittle elements are present).

Earthquake-resistant buildings are:

- Regular in plan and elevation.
- Designed without changes in strength and stiffness in the load-resisting elements.
- Tied together to respond as a unit to the ground shaking.
- Separated from adjacent buildings to avoid pounding.
- Designed without reentrant corners and zones of high stress concentrations.

Significant advances in siting, design, and construction have been made by introducing hanges in practice based on these lessons from past earthquakes.

INTRODUCTION

Every year in the United States, approximately $400 billion are invested in new construction (i.e., new buildings, lifeline systems, and facilities). The following three professional practices are very important in ensuring earthquake safety:

- **Siting**, which establishes the best location with respect to the earthquake hazard for building, lifeline, or facility.

- **Design**, which ensures that the building, lifeline, or facility will be able to withstand the forces and displacements expected to be generated by earthquakes during the lifetime of the structure.

- **Construction**, which transforms drawings and theory and wood, steel, concrete, and masonry into functioning buildings, lifelines, and facilities, for man's benefit over a period of several decades or more.

Every community must solve a number of technical issues inherent in siting, design, and construction, especially in earthquake-prone regions. These issues arise in varying degrees during the construction of structures such as dwellings, public and privately-owned buildings, schools, hospitals, dams, bridges, utility pipelines, airports, sewage treatments facilities, waste repositories, city command centers, and military facilities.

Procedures for siting of each type of structure and setting the seismic design parameters vary markedly. They range from relatively simple procedures for dwellings and ordinary buildings to complex procedures for facilities such as nuclear power reactors. In all cases, some type of design spectrum is derived for each type of structure being constructed in the community. For ordinary buildings, the design provisions of a Building Code provide the generic design spectra; whereas, it is developed for nulear power reactors on the basis of detailed studies prescribed by Appendix A of 10 CFR 100 published in 1973 by the United States Atomic Energy Agency, U.S. Nulcear Regulatory Commissions's Regulatory Guide 161, or other guidelines such as the International Atomic Energy Agency's Safety Guide Series.

PERSPECTIVES ON SITING AND DESIGN

In order to site and design a structure with regard to the earthquake hazard, professionals must acquire and analyze a large body of geologic, geophysical, seismological, and geotechnical information. The database must be adequate for defining:

- the ground motion, which is a function of:
    - seismicity (earthquake activity),
    - source effects,
    - transmission path effects, and
    - local site effects (ground or soil response).

- In addition, the database must be adequate for defining the potential for permanent ground displacements triggered by surface fault rupture, landslides, liquefaction, and subsidence.

The scope of the siting and design studies is directly related to the type of strucute being constructed. It is relatively simple for ordinary buildings and relatively complex for nuclear reactors.

DATABASE FOR EARTHQUAKE HAZARD MITIGATION - The goal of earthquake hazard mitigation is to reduce the destructiveness of future earthquakes. Destructiveness depends on three factors:

- o the magnitude or energy release,
- o proximity of the fault releasing the earthquake, and
- o the extent to which siting and design have correctly assessed the potential ground motion and permanent displacement effects which the structure will be exposed to during its lifetime, which is typically taken as 50 years for ordinary buildings and 40 years for nuclear power plants.

The database should be developed on the following scales, with the scope of the data acquisition program being governed by the type of structure, as noted above. The scales for a nuclear power plant, the most complex structure, typically encompass the following:

- o Regional (map scale of 1:500,000) - to determine all of the factors which contribute to the seismic hazard at a site.
- o Near-regional (map scale of 1:50,000 or smaller) - to determine the seismotectonic model.
- o Site vicinity (map scale of 1:5,000 or smaller) - to determine the physical parameters (and their range of values) that control the site-specific characteristics of ground shaking and ground failure.
- o Site area (map scale of 1:500 or smaller) - to determine the failure mechanisms of specific types of structures, lifeline systems, and facilities.

DATABASE DEVELOPMENT - Data acquisition should be planned so that eight categories of information are collected from past earthquakes:

- o Deaths, injuries, and destructiveness in the affected area of past earthquakes.
- o Failure mechanisms of buildings, lifelines, and facilities located in the affected area of past earthquakes.
- o Design and construction standards that were used in the affected area.
- o Site Parameters which controlled the performance of buildings in the affected area.
- o Spatial dimensions of the affected area.
- o Severity of the primary and secondary physical effects in the affected area and the geologic parameters controlling them.
- o Impact time and duration.
- o Frequency of occurrence of earthquakes of various sizes and specific physical effects such as ground shaking of a certain level or permanent ground displacement of a certain amount.

POOR SITE SELECTION - Experience has shown that structures should not be constructed at locations underlain by young active faults. Such sites should be avoided when possible.

SITE AMPLIFICATION - Experience has shown that structures should not be constructed at locations where the vibration period of the soil deposit is the same as the vibration period of the structure, unless specific engineering solutions are adopted to mitigate the adverse effects. In summary, there are soil-structure combinations that should be avoided when possible to eliminate the possibility of resonance.

CRITICAL RESONANT PERIOD RANGES OF SOIL COLUMNS - Stiff, medium, and soft soil columns have characteristic periods of vibration just as buildings of various heights do. In siting, the objective is to avoid locations where the soil and structure have the same vibration periods. Such a situation can lead to vibrations having very large amplitudes (i.e., resonance).

LIQUEFACTION POTENTIAL - Structures (and especially buried lifeline systems) should not be constructed at locations where liquefaction is likely to occur.

Assessment of the potential for liquefaction (the temporary loss of bearing strength in a water saturated sandy material) at a site is a function of:

- the probability that a certain level of strong ground motion will occur during a specific interval of time, and
- given this level of strong ground shaking, the probability that it will trigger the loss of bearing strength at the site.

Guidelines have been developed for evaluating liquefaction potential at a site. They are based on the number of blows in a standard penetration test (SPT), the grain size, and the depth of the water table at the site.

FACTORS IN DESIGN

For a building, damage (nonlinear behavior) is allowed, but collapse is not. Hence, the design parameters of buildings (e.g., peak ground acceleration, spectrum) are purposely selected to be lower than the actual demand.

For the case of a nuclear power reactor, damage (nonlinear behavior) is not allowed in the design.

DEFORMATION DEMAND - The strength of the building (capacity) must counteract the earthquake load under all loading conditions. The deformation demand (nonlinear behavior) will be small when the capacity exceeds the load and large when the load exceeds the capacity. The design and construction are successful when a building can experience considerable deformation in an earthquake without collapsing.

ROLES OF ARCHITECTS, ENGINEERS, AND URBAN PLANNERS - Architects, engineers, and urban planners have important roles in earthquake-resistant design. The architect deals with individual engineered buildings, focusing mainly on the total building concept and the design of non-structural components. The architect and engineer frequently share the responsibility for earthquake-resistant design. The urban planner contributes to the way groups of engineered and non-engineered buildings are combined to form a street, a community, or a city.

Three considerations dominate for the architect:

1. The building configuration (e.g., the size and shape of the building).
2. The non-structural components.
3. Occupant safety.

The architect and engineer should work together to integrate the functioning parts of a building with its structural skeleton and the dynamic earthquake forces. Frequently, however, they find that these factors introduce conflicts at the concept planning stage that affect the simplicity, regularity, and symmetry of the building. Such conflicts must be resolved in order to achieve satisfactory building performance in an earthquake. Vertical variations in a building are very important because they can introduce regularities in mass, stiffness, and strength. Such irregularities can give rise to large demands in force and deformation, unless they are accommodated in the design process.

The essential elements for a good earthquake-resistant design include:

- o A realistic estimate of the ground motion likely to be experienced during the lifetime of the building and the predominant frequency of the vibration.
- o A sound structural concept for dissipating the seismic energy.
- o An understanding of the way the structure will behave when primary structural elements have yielded during ground shaking.
- o Good detailing to provide a margin of safety.
- o Good quality of construction and inspection to ensure compliance with codes and standards.

The architects and engineers put all their theory and experience into wood, steel, concrete, and masonry. The final test of their work is how the final product--the building-- performs during a damaging earthquake.

GROUND MOTION - The ground motion expected to be transmitted through the base of a building must be specified in the design. The ground motion is a function of the physical parameters of:

- o the earthquake source,
- o the propagation path, and
- o the site geology.

These parameters control the amplitude, frequency composition, and duration of the ground motion that is expected during the useful life of the building. Quantifying these parameters and their variance is an important and challenging part of the design process.

BUILDING REACTION TO GROUND MOTION - The ground motion causes the mass of a building to vibrate, generating inertial forces that are related to the size and shape of the building (i.e, the building configuration). These inertial forces can be quite large. The horizontal or lateral forces of ground shaking use up the strength of the building by bending, shearing, and twisting the columns, beams, floors, and walls. Eventually, the force of gravity acts to pull a weakened and distorted structure down.

Ideally, the building vibrates like a pendulum with a natural period, amplifying the groun motion input at its base.

DEMAND VERSUS CAPACITY - The ground motion load (demand) (see slide 10) must be resisted by the structure. Stiffness, strength, and a material property called ductility are very important properties of the building enabling it to resist the ground shaking. Ductility is the physical property of certain materials like steel which enables it to resist failure until after considerable inelastic deformation has occurred. This type of deformation is planned during the design process as a means of dissipating the seismic energy.

Base isolation is a technique that is currently being used for seismic protection. In base isolation, flexible elements are added between the foundation and the structure to move the vibrational period of the structure to another part of the spectrum, taking advantage of the fact that earthquakes release most of their energy within a fairly narrow vibrational frequency range. Base isolation allows the normal large inertial forces to be considerabley reduced.

STRUCTURAL MATERIALS - Structural materials have a wide range of brittle and ductile properties. Masonary is brittle; whereas, steel is ductile. Wood and reinforced concrete have properties in between masonry and steel.

CONFIGURATION PROBLEMS - Various types of configuration problems are typically faced by the architect. They include:

- o Vertical discontinuities (soft stories, offsets, infills)
- o Plan irregularities (re-entrant corners, unbalanced resistance, diaphragm movement or vibration)
- o Detail problems (strong beam-weak column)

COUPLING STRUCTURAL CONCEPTS WITH BUILDING CONFIGURATION - The architect and engineer can adopt several solutions to solve building configuration problems. They include:

- o Eliminate the problem.
- o Separate the elements.
- o Strengthen weak elements.
- o Transition to adjacent elements.
- o Minimize with base isolation.

NON-STRUCTURAL COMPONENTS - Damage to non-structural components can be equally as disruptive as damage to the structural components of a building. The architect and engineer should work together to solve non-structural

CONCLUSIONS

Siting, design and construction are critically important practices in earthquake-resistant design. Steps should be taken to improve them throughout the Nation.

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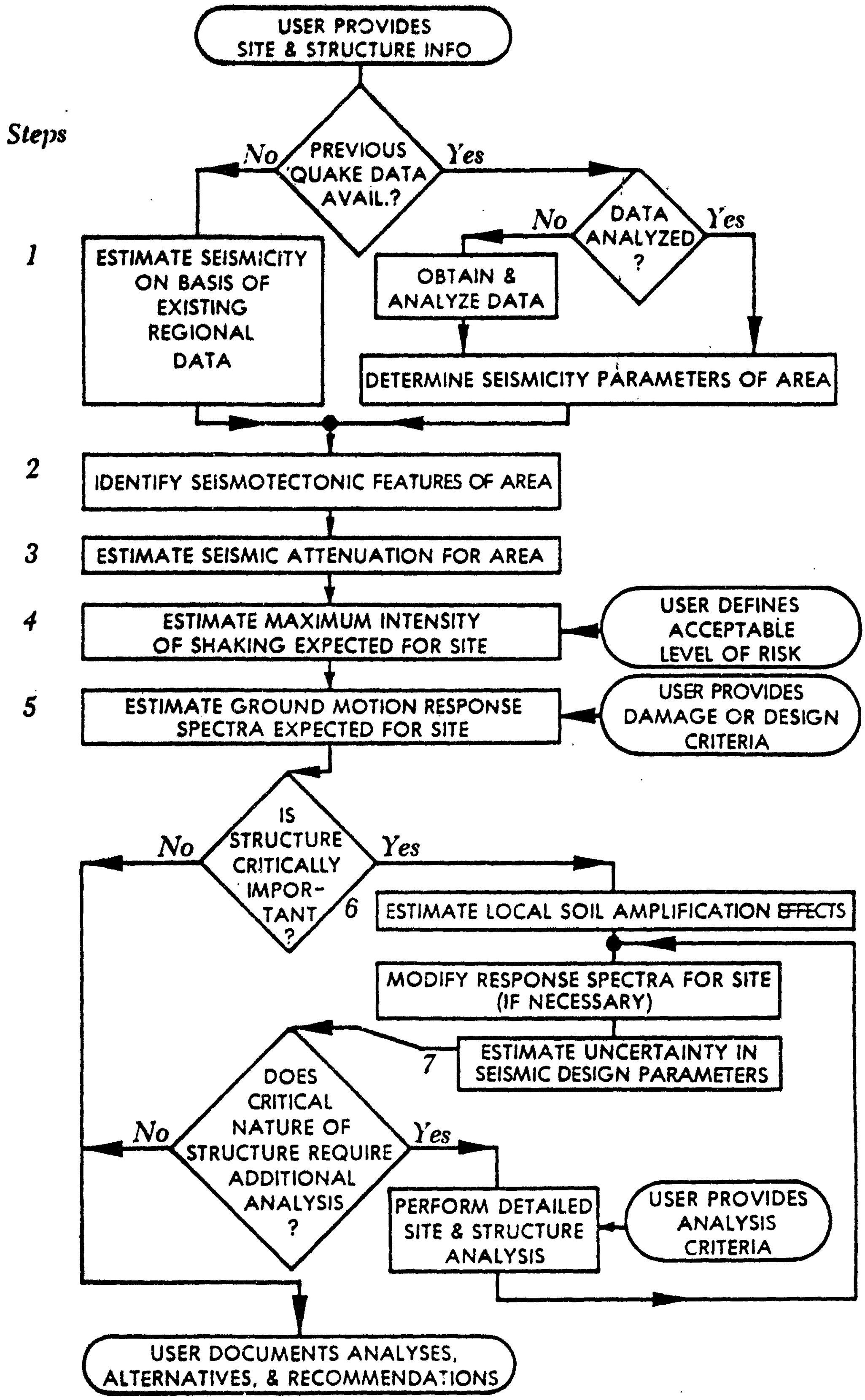


Figure 1: Diagram showing the seven basic steps followed in siting a structure in an earthquake-prone region.

EARTHQUAKE SPECTRA AND DAMAGE

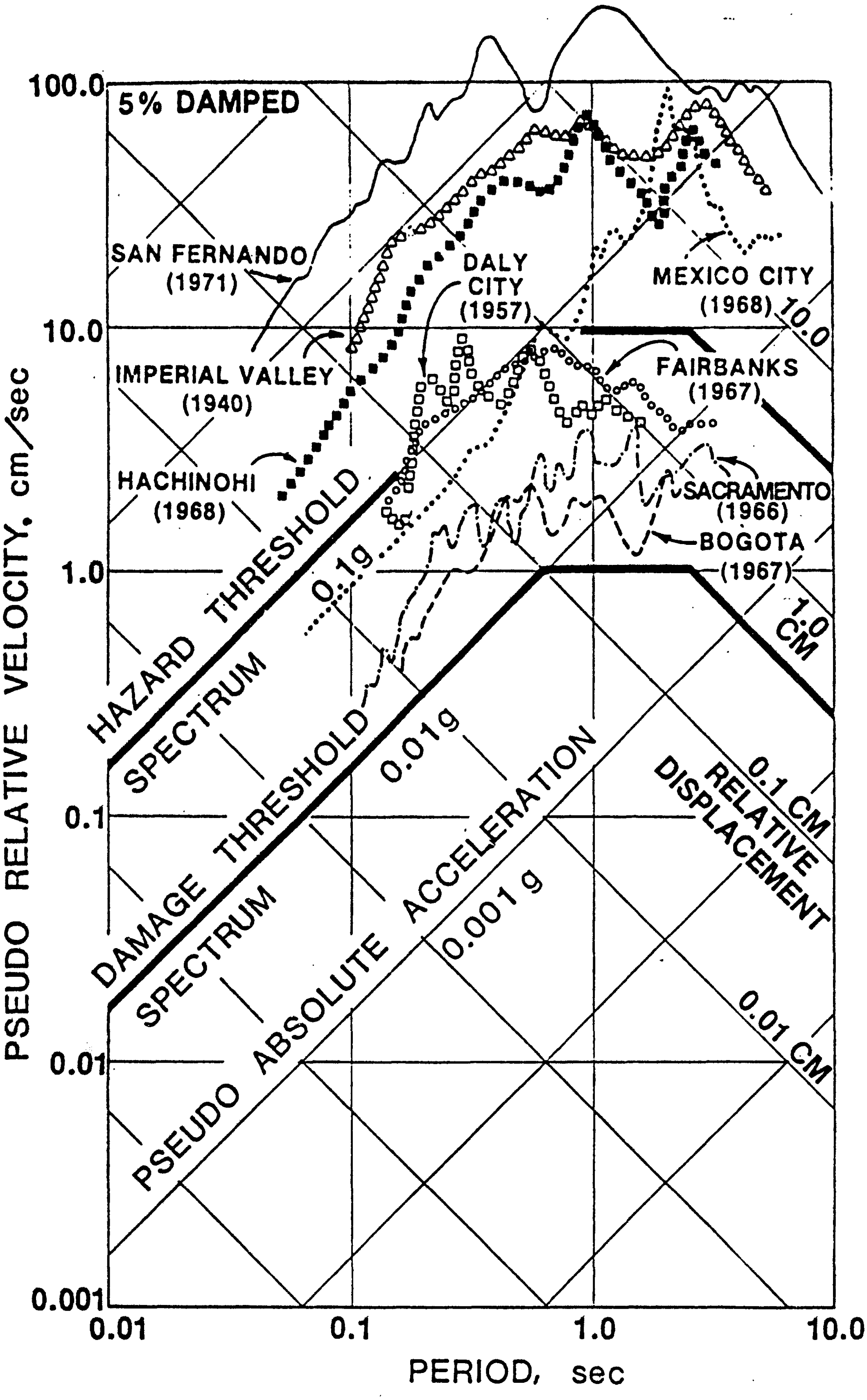
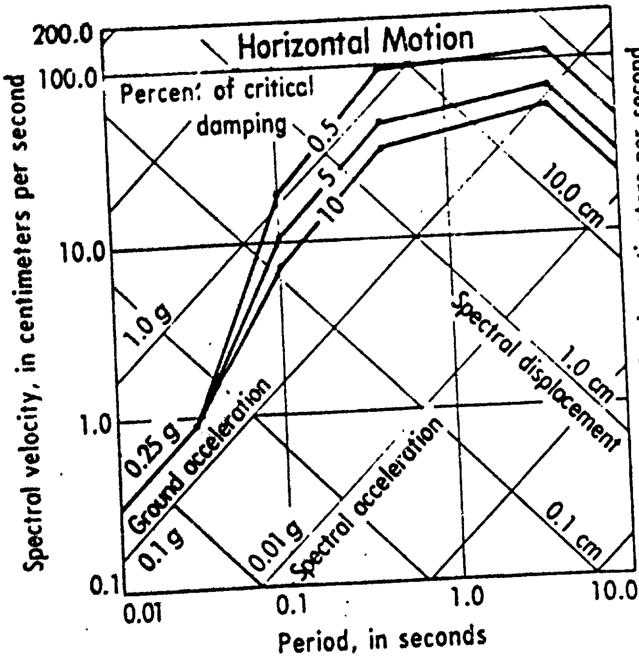


Figure 2: Examples of response spectra derived from strong ground motion records of past damaging earthquakes.



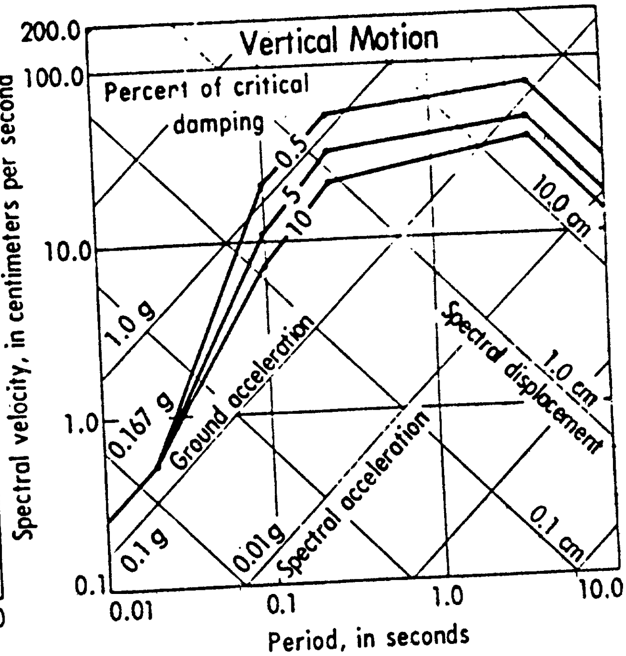


Figure 3: Exampls of smooth, broad-band response spectra used in design of critical facilities. The Nuclear Regulatory Commission's Regulatory Guide 1.60 is the standard for this application.

SITE AMPLIFICATION--AN IMPORTANT CONSIDERATION IN EARTHQUAKE-RESISTANT DESIGN

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ABSTRACT

When analyzing the patterns of damage in an earthquake, physical parameters of the total earthquake-site-structure system are correlated with the damage. Soil-structure interaction, the cause of damage in many earthquakes, involves the frequency-dependent response of both the soil-rock column and the structure. The response of the soil-rock column (called site amplification) is controversial because soil has strain-dependent properties that affect the way the soil column filters the input body and surface seismic waves, modifying the amplitude and phase spectra and the duration of the surface ground motion.

INTRODUCTION

The 19 September 1985 Mexico earthquake reminded earthquake engineers that two frequency-dependent phenomena, site response and structural response, are very important considerations in earthquake-resistant design. The Mexico earthquake reemphasized these facts:

1. The damage to a structure at a site in an earthquake is complexly related to the dynamic frequency-dependent properties of the earthquake source, wave propagation path, and the soil-rock column underlying the structure (Fig. 1). The physical parameters of the total earthquake-site-structure system that contribute most to the potential for damage are those parameters which cause the soil-rock column and the structure to vibrate with the same period (1).

2. The ground motion recorded in an earthquake at a free-field location is the best dynamic representation of how the ground moved--its time histories of acceleration, velocity, and displacement, spectral composition, level of dynamic strain, and duration of shaking. Physical parameters of the source, propagation path, and soil-rock column contribute distinctive frequency-dependent signatures to the ground motion. For example: a) source-increasing the magnitude increases the amplitudes at all periods, enhancing the long periods most, b) propagation path-the path acts like a low-pass filter, attenuating the amplitude of the short periods more rapidly than those of the long periods, and c) site-the soil-rock column acts like a filter, increasing the amplitudes of the surface ground motion in a narrow period band (2,3).

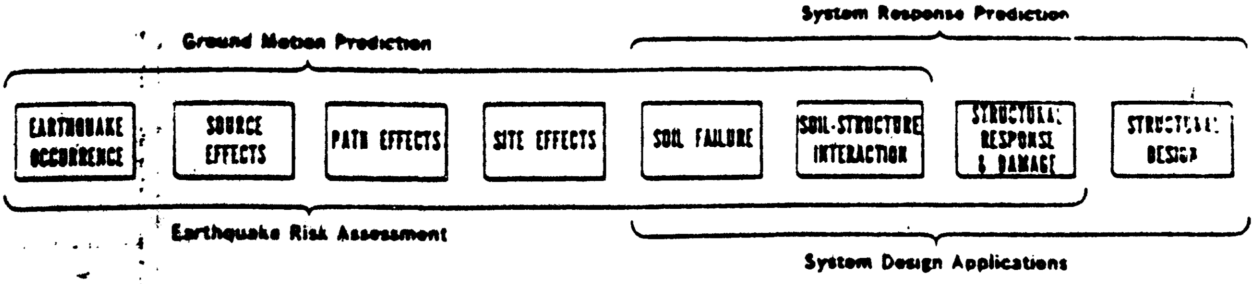

Figure 1.--Schematic illustration of the earthquake-site-structure system. The amplitude, spectral composition, and duration of the ground motion at a free-field location are directly related to physical parameters of the source, propagation path, and the soil-rock column underlying the site.

3. The level of dynamic shear strain and its effects on soil properties are the most controversial aspects of site response. The level of strain induced in the soil column by the ground motion increases as the magnitude increases and decreases as the distance from the center of energy release increases.

4. The response of the soil-rock column depends strongly on the strain-dependent properties of the soil. Depending of the level of dynamic shear strain and the contrast in physical properties of the soil and rock, the soil acts either as an energy transmitter or an energy dissipator. As an energy transmitter, the soil column acts like a filter, modifying the amplitude and phase spectra of the incident body and surface seismic waves (3) and increasing the duration of shaking (4). As an energy dissipator, the soil column damps the earthquake ground motion, transmitting part of the vibrational energy of both the soil column and the structure back into the earth and permitting: vertical movement, rocking, and side-to-side movement of the structure on its base (5).

5. Site amplification, the frequency-and strain-dependent response of the soil-rock column to body and surface seismic waves, increases the surface ground motion in a narrow period band that is related to the thickness, physical properties, and geometry of the soil column. The site transfer function (Fig. 2) is a way to categorize the dominant spectral response in terms of the period band where it occurs: a) <u>short period</u> (0.05 - 0.5 second, b) <u>intermediate period</u> (0.5-3.3 seconds), and c) <u>long period</u> (3.3 - 10 seconds). The dominant spectral response for a site underlain by soil has been as much as 1,000 percent greater than the response for a site underlain by rock; whereas, the level of peak acceleration has been only as much as 250 percent greater (6,7), and in some cases less.

6. The site transfer function depends on many physical parameters, including: level of dynamic shear strain, shear wave velocity, density, material damping, thickness, water content, surface and subsurface geometry of the soil-rock column, and the types of seismic waves that excite the soil-rock column--their wave lenghts and direction of vibration.

7. The response of the structure can also be increased or decreased, depending on the type of structure, its natural period of vibration, the lateral and vertical dimensions and physical properties of the soil-rock

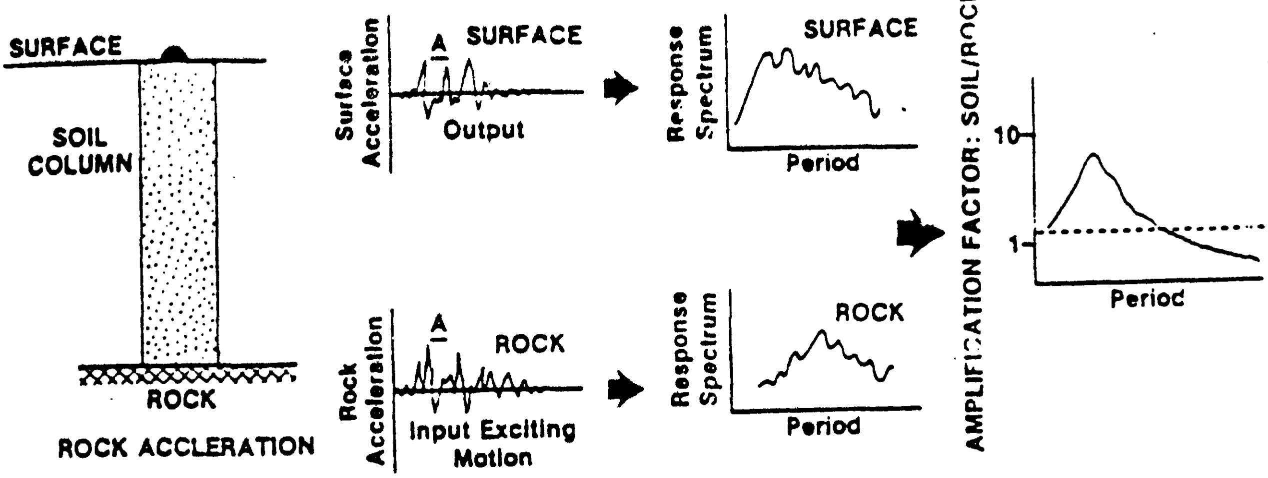

Figure 2.--Schematic illustration showing how a site transfer function is derived. Transfer functions can also be derived for two adjacent soil-rock columns, the procedure used for cited in this paper.

column, and the wave lengths and properties of the incident seismic waves. The worst case is when the fundamental natural period of vibration of the structure is the same as that of the soil-rock column, creating a condition of resonance (Fig. 3).

SITE AND BUILDING PERIODS

Evaluation of what will happen in an earthquake would be easier if the following "ideal" conditions existed:

-- No soil columns. If bedrock were the propagation paths of the body and surface seismic waves, controversy associated with the strain-and frequency-dependent properties of soil columns would be minimized.

-- One building type. If buildings of only one type existed (for example, identical 10-story buildings), then the potential for soil-structure interaction would be greatly restricted.

These "ideal" conditions do not exist; therefore, earthquake-resistant design must take into account the conditions that cause site amplification of ground motion and damaging soil-structure interaction, This means that the wide range of soil columns, the types of buildings, and the physical conditions that cause their responses to occur at the same period must be identified.

A soil column, like a building or structure (see Fig. 3), has a natural period of vibration. The characteristic period of vibration 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 V_s is the shear wave velocity measured at low levels of strain. Soils, depending on their physical

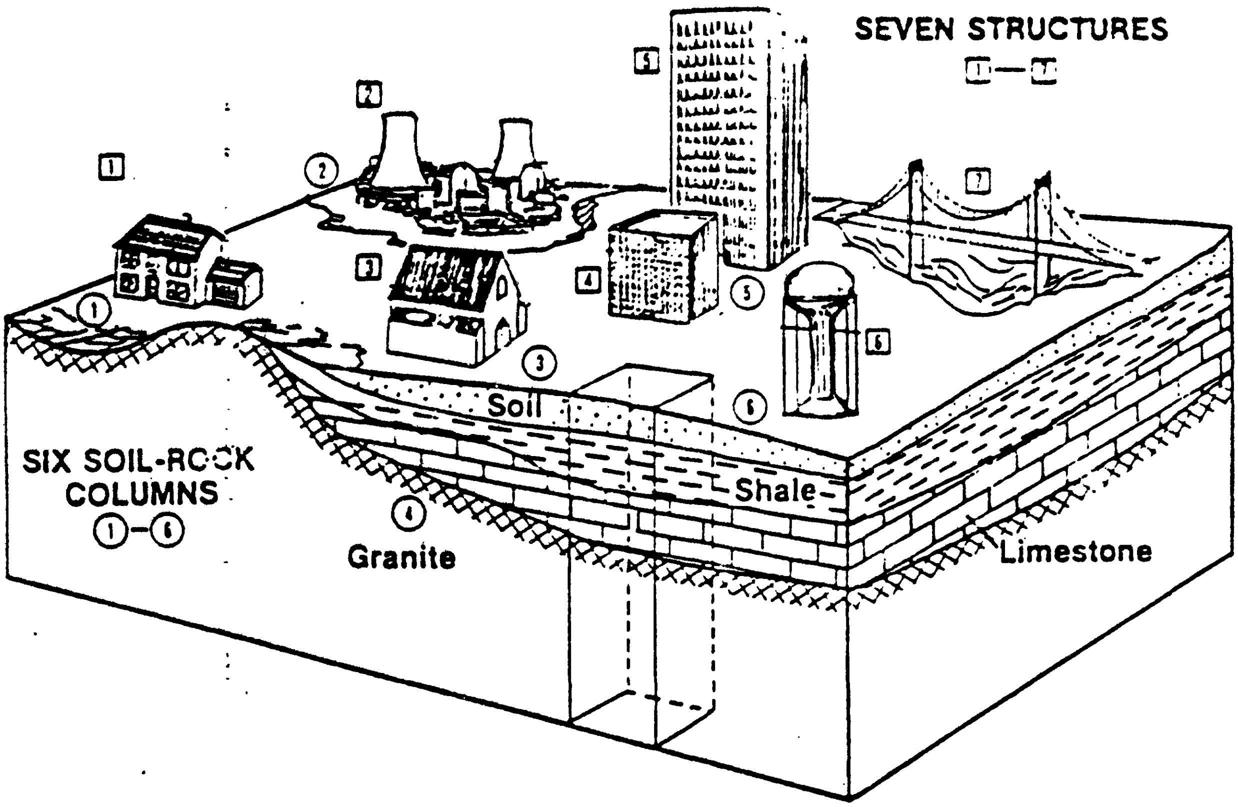

Figure 3.--Schematic illustration showing six soil-rock columns and seven structures. Each soil column has a natural period of vibration (T_s), and each structure has a natural period of vibration (T_b). When T_s and T_b are equal, the potential for severe damage exists.

properties, typically have shear-wave velocities ranging from 50 m/sec to 600 m/sec; whereas, rock-like material and rock have shear wave velocities of 765 m/sec or greater.

Soil columns exhibit properties that are strain-dependent. Laboratory tests (8) have shown that as the level of dynamic shear strain increases the material damping increases and the modulus of shear decreases. The result is that T_s increases as the level of shear strain increases. The basic relation is given by

$$T_s = \frac{4H}{RV_s} \tag{2}$$

where R is an empirical factor (6) having the following values: a) 0.9 for a magnitude 6 earthquake producing a peak effective acceleration of 0.1 g, b) 0.8 for a magnitude 6 earthquake producing a peak effective acceleration of 0.2 g, c) 67 for a magnitude 7 earthquake producing a peak effective acceleration of 0.3-0.4 g.

The fundamental natural period of vibration T_b of a building is given <u>approximately</u> by the relation

$$T_b = \frac{N}{10} \tag{3}$$

where N is the number of stories. However, the actual natural period of a building can be shorter or longer, depending on the engineering design to make the building stiffer or more flexible. Observations from postearthquake investigations have shown that T_b lengthens as the thresholds of various states of damage are reached. In an earthquake, the "worst" case for damage, is when the value of T_s coincides with T_b.

TECHNICAL CONSIDERATIONS IN THE EVALUATION OF SITE AMPLIFICATION

Evaluation of site amplification requires careful consideration of each of the topics discussed below. Limitations on space allow only a few of the pertinent references to be cited.

1. Level of dynamic shear strain and the dynamic physical properties of the soil column--Careful judgment must be used when assessing the level of dynamic shear strain and its effects on the physical properties of the soil column. One of the sources of controversy comes from the fact that laboratory measurements have demonstrated that soils have shear modulii and damping characteristics that depend on the level of strain, suggesting that, under certain conditions, nonlinearities and inelasticities in the soil will attenuate rather than amplify the peak amplitudes of surface ground motions observed at sites underlain by soil. However, empirical ground-motion data representing the high levels of strain produced in the laboratory have not been duplicated by actual strong motion records in past earthquakes. For example, the greatest value of peak ground velocity recorded in the 1971 San Fernando and 1979 Imperial Valley earthquakes is 110 cm/sec. Using the empirical rule that

$$\text{Strain} = \frac{\text{peak velocity recorded at the site}}{\text{shear wave velocity of the soil column at the site}} \qquad (4)$$

the conclusion is that the greatest level of strain induced in soil columns by past earthquakes has been only about 0.5 percent.

Some researchers (for example, 9, 10) have shown that site response is essentially linear up to strain levels of about 0.5 percent for some soil-rock columns and that the epicentral distance to the strain level of 0.5 percent is only a few km (about 1 mi) if the shear wave velocity of the soil column is assumed to be 200 m/sec.

Selection of the dynamic properties of the soil is especially complicated below depths of 30 m (100 ft). For the deeper zone, the average shear wave velocity (V_s) can be estimated fairly accurately from values of the compressional wave velocity (V_p) determined from seismic reflection or refraction surveys or from measurments in boreholes, using a value of 0.4 to 0.45 for Poisson's ratio.

2. Thickness of the soil column--Two different points of view have been used to select the thickness of the soil column. One view (6) considers that the soil column can be terminated without appreciable error when material having a shear wave velocity of about 765 m/sec is reached. The other view (11) considers that the soil column can be terminated without appreciable error only when bedrock having a compressional wave velocity of at least 3,600 m/sec (12,000 ft/sec) is reached. In the first case, surface motions are assumed to be affected mainly by a short soil column,

frequently about 30 m (100 ft) thick; whereas, in the second case, rock motions are assumed to be affected by a much thicker soil column.

3. Near field--Analyses of near-field (that is, locations within 15 km (9 mi) of the source) strong-ground-motion data have been made by a number of investigators (for example, 6, 12, 14). For the near field, these analyses indicate that:

   -- Separation of the frequency-dependent effects of the source from the effects of the soil-rock column is very difficult, because the source effects tend to dominate the path and site effects. The directivity of the source appears to cause most of the large variability in the values of peak ground accelerations, peak ground velocity, peak ground displacement, and spectral velocity. (13).

   -- A "killer pulse" (14), a pulse of approximately 1 second duration that typically does not have the greatest amplitude but which has the greatest kinetic energy, is generated in some cases in the near field as a consequence of the "fling" of the fault. Breakout and stopping phases related to the fault rupture can also be present in the near-field ground motion.

4. Rock Motions--Specification of the ground motions developed in rock by the earthquake source is one of the most difficult task in the analysis of site amplification. The characteristics of surface ground motion depend on the details of the geology of the propagation path, which are usually imprecise. Therefore, analytical calculations must be augmented with a suite of strong motion records acquired in past earthquakes. The ideal data are those for sites underlain by rock located at about the same distance from the zone of energy release and having identical geology for the propagation path as the site being evaluated (2).

5. Aftershock ground motion data--Broadband records of the aftershock sequence of past earthquakes can be used, but the strengths and weaknesses of the analysis procedure must be carefully considered. The strength is that aftershock records have the signature of the travel path and the soil-rock column, only the source parameters differ. The weakness is that the levels of dynamic shear strain developed in an aftershock may cause possible overestimation of the amplification factor and underestimation of the dominant period of site response (15).

6. Angle of incidence--Analysts typically assume vertical incidence of the body waves at the base of the soil column. This assumption, if violated, does not introduce significant error (3).

7. Variability in the mean site transfer function--Several investigators (for example, 2, 3) have shown that the site transfer function in the intermediate-and far-fields is fairly repeatable. The degree of repeatability of the site transfer function for the near field and for conditions of strain exceeding 0.5 percent is unknown.

EMPIRICAL DATA ON SITE AMPLIFICATION

Worldwide

Scientists and engineers throughout the world have recognized and documented site amplification phenomena since the 1800's (7, 13, 16, 17, 18, 19, 20, 21). Four classic examples are described below in terms of the spectral response relative to rock and the period band of dominant response:

1. The 1967 Caracas, Venezuela earthquake--Soil-structure interaction occurred in Caracas, 56 km (35 mi) from the epicenter of this moderate (magnitude 6.4) earthquake. Tall buildings (14 stories and greater) sited on soil columns of at least 160 m (520 ft) thickness were damaged severely. The dominant response occurred in the intermediate period band, centered around 1.2-1.6 seconds (20).

2. The 1970, Gediz, Turkey, earthquake--Soil-structure interaction caused the collapse of a 1-story garage and paint workshop (a part of the Tofias automobile factory) located 225 km (135 mi) from the epicenter of this large (magnitude 7.0) earthquake. The cause was the similarity of the predominant periods of: a) the bedrock motions, b) the response of the 120-135 m (390-440 ft) column of alluvium, and c) the response of the building, all of which occurred in the intermediate period band centered around 1.2 seconds (21).

3. The 1976 Friuli, Italy, earthquake--Site amplification of a factor of 4 occurred in the short-to-intermediate period band (0.2-0.7 seconds) for a site underlain by 15 m (50 ft) column of alluvium located 25 km (15 mi) from the epicenter. The input rock accelerations ranged from 0.1 g to 0.53 g (19).

4. The 1985 Mexico earthquake--This great (magnitude 8.1) earthquake produced two surprises: a) the low value of peak acceleration (0.18 g) in the epicentral region, and b) the high (0.18 g) value of peak acceleration in certain parts of Mexico City located 400 km (250 mi) from the epicenter. Soil-structure interaction caused extensive damage to 5-20 story buildings sited in the lake bed zone of Mexico City (22). The largest ground motions in Mexico City occurred at sites underlain by a 50-meter-thick column of soft lake bed deposits having a shear wave velocity of about 100 m/sec. The dominant site response occurred at 2-seconds, an amplification of about a factor of 5 relative to the level of ground motion observed at nearby sites underlain by stiffer, rock-like material.

United States

Since the 1960's, many investigators have studied site amplification phenomena in various parts of the United States. Results obtained in each area are summarized below with representative references:

1. San Francisco Bay region--The most significant contributors to knowledge of site amplitude were: the 1906 San Francisco earthquake, a) the 1957 Daly City earthquake, and b) the extensive program of geologic and engineering seismology data acquisition conducted by the U.S. Geological Survey in the 1970's. The most significant results included:

-- Inferences in 1908 that the soil-rock column underlying a structure can have a significant effect on the surface ground motions and the damage patterns (23).

-- Strong ground motion data from the 1957 Daly City earthquake that provided a basis for concluding that the amplitude and spectral composition of the ground motions varied as a direct function of the propagation path and the physical properties of the soil-rock column (16).

-- Verifying that each geologic unit in the San Francisco Bay region has a characteristic and predictable response to low-strain seismic excitation (24, 25).

-- Demonstrating that San Francisco Bay mud exhibits the most spectacular site response, amplifying the short-period energy by a factor of 10 or more under conditions of low-strain ground shaking. Other soil-rock columns also caused amplification, mostly in the short- and-intermediate period bands (24, 25).

2. Los Angeles Region--The most significant contributors to knowledge of site amplification were: a) the 1971 San Fernando earthquake which produced 241 3-component strong motion accelerograms for buildings and free-field locations within 75 km (45 mi) of the epicenter of a magnitude 6.4 earthquake, b) the extensive program to monitor the aftershocks of the San Fernando earthquake at more than 100 locations, and c) the comprehensive program of data acquisition conducted by the U.S. Geological Survey in the 1970's and 1980's. Important results included:

-- Similar site transfer functions derived from ground motion data recorded from the mainshock, selected aftershocks, and nuclear explosions even though the levels of rock accelerations and strain varied markedly (10, 18).

-- Amplification of short-period seismic energy along the boundary of the San Fernando valley, a zone of damage (Hays, 1977), and in Glendale (26).

-- Amplification of the long period surface waves by the thick alluvium in the Los Angeles basin (27).

-- Amplification of the ground motion by some topographic highs (28).

-- Amplification occurring at soil sites in the Long Beach and Los Angeles areas (18). The short-, intermediate-, and long-period bands were enhanced by factors ranging from 2 to 5.

3. Nevada--The Ground Motion and Structural Response program of the U.S. Atomic Energy Commission, conducted in the 1960's and 1970's, was the main contributor to knowledge of site amplification. More than 3000 strong motion records were obtained at locations such as Tonopah, Las Vegas, and Beatty where the regional geology and the soil-rock columns were fairly well known. The most significant results included:

-- Documentation of the similarities of the strong ground motion records of earthquake and nuclear explosions within a few hundred miles of the source (2,4).

-- Acquisition of site amplification data at locations having a wide range of soil-rock columns (3) experiencing levels of strain ranging from 0.001 to 0.5 percent (10).

-- Demonstration of classic short-period body-wave amplification in Tonopah where the soil amplification factor was 7 (3).

-- Demonstration of classic intermediate-to-long-period surface-wave amplification in Las Vegas where the soil amplification factor was 10 (29).

-- Demonstration of short-period site amplification as a function of depth at Beatty where the rock motion were reduced by a factor of 4 at periods equal to T_s (30).

4. Seattle, Washington--Ihnen and Hadley (31) modeled the strong ground motion of the 1965 Seattle earthquake using a ray tracing technique. Their results indicated that the thick, soft soil deposits of the Duwamish River caused short-to-intermediate period site amplification of a factor of about 5 in western Seattle, the area sustaining the greatest damage in 1965.

5. Wasatch Front, area, Utah--The extensive program of data acquisition conducted by the U.S. Geological Survey in 1970's and 1980's provided the main knowledge of site amplification along the Wasatch front. Salt Lake City, Ogden, and Provo are adjacent to the 370-km-long (222 mi) Wasatch fault zone. These cities are founded on several soil deposits, ranging from coarse gravels and sands to fine grained silts and clays, deposited as lakes filled the Great Salt Lake basin in the Pleistocene epoch. Important results included:

   -- For distances of about 30 km (18 mi) from the Wasatch fault zone in Salt Lake City, Ogden, and Provo, site amplification increases as distance from the fault increases. Site response of as much as a factor of 10 (relative to rock on the Wasatch front) occurs at sites in the center of the valleys underlain by a thick column of soft, water-saturated silts and clays. The dominant period of response occurs in the intermediate-period band, centered around 1 second. Site response is less--about a factor of 2 in the intermediate-period band for sites underlain by coarse gravels and sands close to the fault zone (9, 32).

6. Eastern United States--The soil-rock columns in many parts of the Eastern United States (for example, Memphis, St. Louis, Boston) have physical properties that will cause site amplification in an earthquake. Further research is needed to quantify the potential for damage.

SUMMARY AND CONCLUSIONS

On the basis of empirical data from past earthquakes, buildings located on soil deposits may be susceptible to damage from earthquake ground shaking if the soil-rock column has the physical properties required to amplify the ground motion. The damage to a building can be severe when the dominant periods of the site response and the building response coincide. Urban development should: a) identify locations having the potential for soil-structure interaction, and b) ensure that earthquake-resistant design criteria are adequate to withstand the forces that can be generated by this phenomenon. Evaluation of site amplification effects is an important part of the overall assessment of risk in an urban area. Although some uncertainty and controversy exist, a number of urban areas in the United States appear to have soil-rock columns that will amplify earthquake ground motions.

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ZONATION STUDIES IN WORLD-WIDE SEISMOTECTONIC ANALOGS: PRE- AND POST-EARTHQUAKE ENVIRONMENTS

ABSTRACT

This paper reviews the basic principles of seismic zonation--the multidisciplinary process that leads to the division of a region into smaller areas expected to experience the same relative severity of an earthquakes physical effect such as ground shaking. Since the original pioneering research by Japanese scientists and engineers in the early 1900's, many significant advances in understanding have been made. The time seems to be right for renewed efforts in seismic zonation to be made worldwide.

1. WHAT IS TO BE DONE?

1.1 Design Goal

The goal is to devise a set of standard procedures that can be used throughout the world to produce seismic zonation products. Products produced in a seismic microzoning study are applied in land-use, building codes, design and construction practices, repair and strengthening of existing buildings, and response and recovery planning. These applications can save lives and economic resources.

Although the pre-earthquake environment is more optimal, experience shows that seismic zonation studies are accepted more readily as a strategy for reducing losses from earthquake hazards in the post-earthquake environment. Political considerations are usually less of an impediment in the post-earthquake environment.

1.2 Background

Seismic zonation, 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 and assessing the risk in an urban area. Seismic zonation 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 him to select the most suitable part of the area for the proposed use.

2. HOW WILL IT BE DONE?

2.1 Compilation of Seismic Zonation Experience

Seismic zonation has been performed in many countries throughout the world. However, there is no standard procedure for seismic zonation, and the results have varied widely from country to country (see proceedings of the three international conferences on seismic zonation held in the United States and the proceedings of the zonation conference held in Algeria).

2.2 Technical Procedure

The key to the creation of a standard procedure in seismic zonation is to obtain explicit answers to the following 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., next 50 years)?
-- How do the physical effects vary spatially and temporally?
-- How have these physical effects impacted various types of buildings and lifeline systems?

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

1) Evaluation of seismic hazards on a regional scale: (a map scale of about 1:100,000 to 1:1,250,000). 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 tasks such as the following are required:

   a. Compilation of a catalog and map of the prehistorical, historical, and current seismicity.

   b. 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.

   c. Preparation of a seismotectonic map showing the location of active faults and their correlation with seismicity.

   d. Preparation of a map showing seismogenic zones and giving the magnitude of a maximum earthquake and the frequency of occurrence for each zone.

   e. Specification of regional seismic wave attenuation laws and their uncertainty.

   f. 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 zonation study integrates the seismotectonic and other physical data acquired in the region of the study (Part 1 above) with site-specific data acquired in the urban area to produce seismic zonation maps. Technical tasks such as the following are required:

a. 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.

b. 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 for a range of seismic loads.

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

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

e. Preparation of a map showing the potential for seismically-induced landslides.

f. Analysis of the vulnerability of various types of buildings and lifeline systems under a range of seismic loads.

3. WHAT LEADS US TO BELIEVE IT CAN BE DONE?

3.1 Basic Data

The basic data required for seismic zonation are available in many countries throughout the world; what is missing is a standard procedure which must be addressed eventually. Zonation on the regional and urban scales requires the best available information on: 1) seismotectonics 2) the nature of the earthquake source zone, 3) seismic wave attenuation, 4) local ground response, and 5) building and lifeline response.

3.2 Scientific and Engineering Problems

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. Considerations of structural response and potential vulnerability will not be discussed here. Similar technical problems can be stated for the ground-failure hazard.

Seismicity - The record of historical seismicity in both the United States and other countries varies considerably in length and completeness. Lack of completeness can introduce biases in statistical analyses unless careful judgments are made. Incorporating geologic evidence of recent faulting as well as geodetic data improves the likelihood of establishing the best possible recurrence rates for earthquakes. 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. Use of the record of historical seismicity alone may cause underestimation of the maximum magnitude.

The issues include the following:

a. 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?

b. Can the seismic cycle of individual fault systems be determined accurately and, if so, can the point in the cycle be specified?

c. 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?

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

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

Seismogenic Zones - No standard method has been adopted for delineating seismogenic zones. Usually, each cluster of earthquake foci on 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 incorrectly combined and the resultant analysis will suggest some average but nonexistent physical condition. In defining seismogenic 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. Although time-dependent models are now available, earthquakes are commonly assumed to have equal probability of occurrence 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.

The technical issues include the following:

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

b. 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 particular seismic source zone?

c. 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 important yet most difficult parts of the problem of constructing a ground-shaking hazard map. The empirical strong ground motion 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 have been acquired in the near field in the 1979 Imperial Valley, California, earthquake and in other locations worldwide. These data have reinforced current thinking in some areas and revised it in others, but have not resolved all of the controversial issues concerning seismic wave attenuation. Frequency-dependent effects of the transmission path on earthquake ground motion have not been quantified fully because of limited data. Observational and instrumental data 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 considerably from region to region, and that Q is frequency dependent.

Attenuation curves are required to specify how values of peak ground motion (or spectral velocity ordinants) decrease as distance from the causative fault increases. Such curves are essential when constructing a zoning map of the peak-acceleration ground-shaking hazards. The problem is that many peak-amplitude attenuation curves having substantial differences exist in the literature. The question of magnitude dependence of attenuation is important in probabilistic ground-shaking hazard estimation because it sharply influences the estimated level of maximum ground motion in two cases: 1) areas having a high rate of seismicity, and 2) when long periods of time are considered.

The technical issues include:

a. 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?

b. Do values of peak ground-motion parameters or spectral velocity ordinants saturate at large magnitude?

Local Ground Response - Since the early 1900's, literature of earthquake engineering and engineering seismology has recognized and documented that structures founded upon unconsolidated material (soil) are damaged more frequently and usually more severely in earthquakes than structures founded on rock. The damage distribution on many occasions (for example, in the 1967 Caracas, Venezuela, and the 1985 Mexico earthquakes) has been recognized as being related to site geology. Many past studies have used empirical ground-motion data and analytical models to define the frequency-dependent effects that have been and still are 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-magnitude earthquakes will resolve these arguments.

The technical issues include the following:

a. For various soil types, is there a discrete range of peak ground-motion values and levels of dynamic shear strain where the ground response is repeatable and essentially linear? Is there a range where nonlinear effects dominate?

b. 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 response characteristics of ground motions in a geographic region for the fault-site geometries?

c. Can the variation of ground motion with depth below the surface be modeled accurately in order to estimate the ground-shaking effects on underground lifeline systems?

d. To what extent can site effects be predicted and which models are most effective?

3.3 Seismotectonic Analogs

The optimal approach is to select countries that have analogous seismotectonic settings. Most of the zones of seismic activity in the United States have counterparts and analogs in other areas of the world. Much more can be learned about the tectonic setting, earthquake mechanics, earthquake hazards, and risk for parts of the United States by studying tectonic analogs in other countries. Certain aspects of source zones in the U.S. that are not clearly understood (i.e., overburden masking basement feature, lack of long historic record of seismicity, etc.) become impediments or road-blocks to understanding, particularly if efforts are concentrated solely on specific features in the U.S. Critical keys to the understanding of major strike-slip faults like the San Andreas fault may come from research and field mapping of similar features in Turkey, Guatemala, New Zealand, Venezuela, the Philippines, Japan, Alaska, Iran, Pakistan, western China, and the U.S.S.R. Similar statement can be made for normal and thrust faults. A comparison of some of these fault systems indicates that parts of them are in various stages of their earthquake cycle. By studying analogous critical earthquake-generating features in other countries, it may be possible to "catch" forerunning or precursory features of large shocks and to apply that experience prior to the occurrences of the next large earthquake on, say, the San Andreas fault or other fault systems in the U.S.

Intraplate earthquakes and the state of stress in Australia, Canada, northern Europe, the U.K., parts of Africa, and peninsular India show many similarities to those associated with the Central and Eastern U.S. Many shocks in those areas seem to occur along old fault systems that have moved many times throughout geologic history in response to various plate-tectonics events. The configuration of major tectonic elements and the reactivation of fault systems in the Southeastern U.S., the site of the Charleston earthquake in 1886, are similar to those of west Africa near Accura, Ghana, and the Benue trough of Nigeria. The tectonic setting of the New Madrid seismic zone in the Central U.S. is similar to that of the seismic zone that extends into the interior of Australia near Adelaide. Several zones of intraplate shocks are similar to those of the eastern and Central U.S. in that they are characterized by very large areas for a given level of energy release.

A great deal can be learned from studies in other countries about the repeat time of large earthquakes along given segments of strike-slip and convergent plate boundaries. The average repeat time is a function of the long-term rate of plate movement and the geometry of the rupture zone. Variations in repeat time at a given place appear to be associated with the length of the rupture zone and the amount of seismic slip associated with the last large shock in that zone.

Since the historic record of earthquakes along the Alaska-Aleutian arc is so short, information from convergent zones near Japan, New Zealand, India, Pakistan, the U.S.S.R., the Lesser Antilles, Mexico, Central and South America, and other similar areas can be applied to earthquake-related problems for Alaska and the Aleutians. Similarly, the unusual style of plate motion to the north of Puerto Rico and the Virgin Islands--thrust faulting on nearly horizontal planes with the slip vector nearly parallel to the plate boundary--is similar to that in the western most Aleutians and in the Andaman Islands.

4. WHAT IS THE BENEFIT?

4.1 Potential Applications of Seismic Zonation Products

Applications of seismic zonation products (maps, data, analyses) can be made in terms of land-use, building codes, construction practices, repair and strengthening of existing buildings, and response and recovery planning. The benefits in any given country where seismic zonation has been performed include:

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

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

c. Improving design and construction practices for new buildings, specifying options for alternatives to current practices that might be more effective in ensuring high quality.

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

e. Evaluation of plans for emergency response and disaster recovery.

4.2 Implementation

Three groups of professionals will implement the new knowledge provided by seismic zonation: the design professional, the urban and regional land use planner, and the emergency manager.

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DESIGN & CONSTRUCTION OF EARTHQUAKE-RESISTANT BUILDINGS

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I. **Earthquake Damage Mechanisms**

A. Mitigation Strategies - New & Existing buildings

II. **Response of Buildings to Ground Motion**

A. Inertial forces

B. Period & Resonance

C. Damping

D. Ductility

E. Torsion

F. Strength & Stiffness

G. Resistant Systems

H. Load Path & Redundancy

III. **Development of Seismic Code Provisions**

A. Historical Background

B. Building Codes Used in Central U.S. (see p. 2)

IV. **Review of Latest Seismic Code Provisions**

A. 1988 NEHRP Recommended Provisions (see p. 3 - 5)

B. 1988 Uniform Building Code (see p. 6 - 9)

V. **Class Room Exercises Using Latest Seismic Code Provisions**

Building Codes Used in Central United States. (Information from Directory of Building Codes & Regulations, 1989 Edition, published by National Conference of States on Building Codes & Standards, Inc.) Notes: CABO - One & Two Family Dwelling Code; NBC - National/Basic Building Code; SBC - Standard Building Code; UBC - Uniform Building Code.

Jurisdiction	State Residential	City Residential	State Commercial	City Commercial
Arkansas[1]	1982 SBC[2]	---	1982 SBC	---
Little Rock	---	1982 SBC[3]	---	1982 SBC[3]
Illinois	None	---	None	---
Chicago	---	1988	---	1988
Indiana[1]	1987 CABO[4]	---	1988 UBC[5]	---
Indianapolis	---	1986 CABO[6]	---	1988 UBC
Kentucky[1]	1987 CABO 1987 NBC	---	1987 NBC[7]	---
Mississippi[8]	None	---	None	---
Jackson	---	None	---	1988 SBC
Missouri	None	---	None	---
Kansas City	---	1983 CABO	---	1982 UBC
St. Louis	---	1987 NBC	---	1987 NBC
Tennessee[9]	None	---	1988 SBC	---
Memphis	---	1982 SBC	---	1982 SBC
Nashville	---	1986 CABO	---	1985 SBC[10]

[1] Mandatory statewide code for both residential and commercial buildings.

[2] Locals may amend with state approval.

[3] With 1983 supplement.

[4] Locals may not amend.

[5] With 1989 state amendments.

[6] With 1987 state amendments.

[7] With 1988 state amnedments.

[8] Mandatory statewide minimum code (SBC) for state buildings only.

[9] Mandatory statewide code for commercial buildings.

[10] With 1987 city/county amendments.

General Summary of 1988 NEHRP Recommended Provisions
(Consult provisions for details, exceptions, etc.)

Exemptions

Buildings for agricultural use and one- and two-family dwellings that are located in map areas having a value of A_v less than 0.15.

Selection of Lateral Force Procedure

NEHRP provisions base the selection of lateral force procedures (equivalent or dynamic) on Seismic Performance Categories, and in higher categories, on irregularity designations. The level of seismicity and Seismic Hazard Exposure Group are used to assign buildings to Seismic Performance Categories (see table below).

Seismic Performance Categories

	Seismic Hazard Exposure Group		
Value of A_v	I	II	III
$0.20 \leq A_v$	D	D	E
$0.15 \leq A_v < 0.20$	C	D	D
$0.10 \leq A_v < 0.15$	C	C	C
$0.05 \leq A_v < 0.10$	B	B	C
$A_v < 0.05$	A	A	A

Seismic Hazard Group III includes buildings having essential facilities for post-earthquake recovery (medical facilities, fire and police facilities, etc.)

Seismic Hazard Group II include buildings that constitute a substantial public hazard because of occupancy or use (public assembly with a capacity greater than 300 persons, jails, power generating stations, etc.)

Seismic Hazard Group I include all other buildings not classified in Group II or III.

Design Base Shear, V

$$V = C_s W$$

where C_s = seismic design coefficient; and
W = total dead load and applicable portions of other loads.

Seismic Design Coefficient, C_s

$$C_s = 1.2\ A_v S/RT^{2/3}$$

where A_v = effective peak velocity-related acceleration;
S = coefficient based on soil profile characteristics;

R = response modification coefficient based on type of structural system; and
T = fundamental period of the building.

C_s need not be taken greater than $2.5\ A_a/R$.

<u>Building period, T</u>

For buildings in which the lateral force resisting system consists of moment resisting frames capable of resisting 100 percent of the required lateral force,

Empirical method: $T = C_t (h_n)^{3/4}$

where C_t = 0.030 for concrete frames,
C_t = 0.035 for steel frames, and
h_n = building height.

For all other buildings, $T = 0.05\ h_n/L^{0.5}$
where L = overall length (ft) of the building at the base in the direction under consideration.

<u>Site coefficient, S</u>

Four values of site coefficients ranging from 1.0 to 2.0 are specified for different soil conditions. For soil type 1, S = 1.0; for soil type 2, S = 1.2; for soil type 3, S = 1.5; for soil type 4, S = 2.0.

<u>Response Modification Coefficient, R</u>

Values of R are specified for different structural systems and range from 1-1/4 to 8. For example, for a ductile moment-resisting steel-frame, R = 8; and for a reinforced masonry bearing wall building, R = 3.5.

<u>Total Gravity Load, W</u>

W is the total dead load and applicable portions of other loads (i.e., a minimum of 25% of the floor live load in storage and warehouse occupancies; a load of 10 psf where a partition load is used in the floor design; the snow load where it is greater than 30 psf, etc.)

<u>Vertical Distribution of Lateral Forces</u>

The lateral force, F_x, induced at any level, is:

$$F_x = C_{vx} V$$

where $$C_{vx} = \frac{w_x h_x^{\,k}}{\sum_{i=1}^{n} w_i h_i^{\,k}}$$

w_i & w_x = portion of W located at level i or x;

h_i & h_x = height above the base to level i or x;

k = an exponent related to the building period as follows:

For buildings having a period of 0.5 seconds or less, k = 1.
For buildings having a period of 2.5 seconds or more, k = 2.
For buildings having a period between of 0.5 and 2.5 seconds, may be taken as 2 or may be determined by linear interpolation between 1 and 2.

Horizontal Distribution of Shear

The seismic design story shear in any story, V_x, is determined as:

$$V_x = \sum_{i=x}^{n} F_i$$

Design story shear, V_x, is distributed to various vertical elements according to the relative stiffnesses of the vertical elements and the diaphragm.

Accidental torsion - calculated center of mass moved 5% of plan dimension. When torsional irregularity exists and in various seismic performance categories, an amplification factor is applied.

Overturning

Overturning moments are determined as follows:

$$M_x = K \sum_{i=x}^{n} F_i \ (h_i - h_x)$$

where K = 1.0 for the top 10 stories,

K = 0.8 for the 20th story from the top and below, and
K = a value between 1.0 and 0.8 determined by a straight line interpolation for stories between the 20th and 10th stories below the top.

Drift Determination and P-Delta Effects

Story drifts and, where required, member forces and moments due to P-delta effects must be determined. Allowable story drifts are based on the type of building and the Seismic Hazard Exposure Group.

Orthogonal effects

In buildings assigned to Category D or E, the critical load effect due to the direction of application of seismic forces on the building must be considered according to criteria specified.

General Summary of Earthquake Provisions - 1988 Uniform Building Code
(Consult 1988 UBC for detailed provisions, exceptions, etc.)

Exemptions

One- and two-family dwellings in Seismic Zone 1.

Selection of Lateral Force Procedure

1. Static: a. All structures, regular or irregular, in Zone 1 and in Occupancy Category IV in Zone 2.

   b. Regular structures under 240 ft. in height.

   c. Irregular structures not more than 5 stories nor 65 ft. in height.

2. Dynamic: a. All structures 240 ft. or more in height except as provided above in a.

   b. Various irregular structures or structures with irregular features.

Regular & Irregular Structures

Regular structures -- no significant physical discontinuities in plan or vertical configuration.

Irregular structures: Vertical irregularities -- soft or weak stories; large changes in mass; large discontinuities in dimensions or in-plane locations of lateral-load-resisting elements. Plan irregularities -- torsion irregularity; reentrant corners; diaphragm discontinuity; out-of-plane offsets; nonparallel systems.

Design Base Shear, V

$$V = ZICW/R_W$$

where Z = seismic zone factor;
I = importance factor;
C = coefficient dependent on soil conditions & period of structure;
W = total seismic dead load; and
R_W = coefficient which represents the ductility of the structural system.

Seismic Zone Factors, Z

Zone	Factor, Z
1	0.075
2A	0.15
2B	0.20
3	0.30
4	0.4

Importance Factors, I

Occupancy Category	Factor, I
I. Essential facilities	1.25
II. Hazardous facilities	1.25
III. Special occupancy structures	1.00
IV. Standard occupancy structures	1.00

Coefficient, C

$$C = 1.25\ S/T^{2/3}$$

where S = site coefficient for soil characteristics; and
T = fundamental period of vibration (seconds) in the direction under consideration.

Value of C need not exceed 2.75 and may be used for any structure without regard to soil type or structure period.

Except as provided, the minimum value of C/R_w shall be 0.075.

Structure period, T

Empirical method: $T = C_t(h_n)^{3/4}$

where C_t = 0.035 for steel moment-resisting frames,
C_t = 0.030 for reinforced concrete moment resisting frames,
C_t = 0.020 for all other buildings, and
h_n = building height.

Alternative C_t provided for structures with concrete or masonry shear walls.

Site coefficient, S

Four values of site coefficients ranging from 1.0 to 2.0 are specified for different soil conditions. For soil type 1, S = 1.0; for soil type 2, S = 1.2; for soil type 3, S = 1.5; for soil type 4, S = 2.0.

Structural system coefficient, R_w

Values of R_w are specified for different structural systems and range from 4 to 12. For example, for a ductile moment-resisting steel-frame, R_w = 12; and for a reinforced masonry bearing wall building, R_w = 6.

Seismic dead load, W

W is the total dead load and applicable portions of other loads (i.e., a minimum of 25% of the floor live load in storage and warehouse occupancies; a load of 10 psf where a partition load is used in the floor design; the snow load where it is greater than 30 psf, etc.)

Vertical Distribution of Lateral Forces

$$V = F_t + \sum_{i=1}^{n} F_i$$

where $F_t = 0.07TV \leq 0.25V$. If $T \leq 0.7$ sec, $F_t = 0$.

$$F_x = \frac{(V - F_t)\, w_x h_x}{\sum_{i=1}^{n} w_i h_i}$$

Horizontal Distribution of Shear

Design story shear, V_x, distributed to various elements according to their rigidities.

Accidental torsion - calculated center of mass moved 5% of plan dimension. When torsional irregularity exists, an amplification factor is applied.

Overturning

Structure must be designed to resist overturning moments caused by F_t and F_x which act on levels above the level under consideration.

Special combinations of loads and detailing requirements are specified where lateral load-resisting element is discontinuous.

P-delta effects - must be included in determining member forces and story displacements where significant.

Drift limitations

For buildings less than 65 ft. in height,

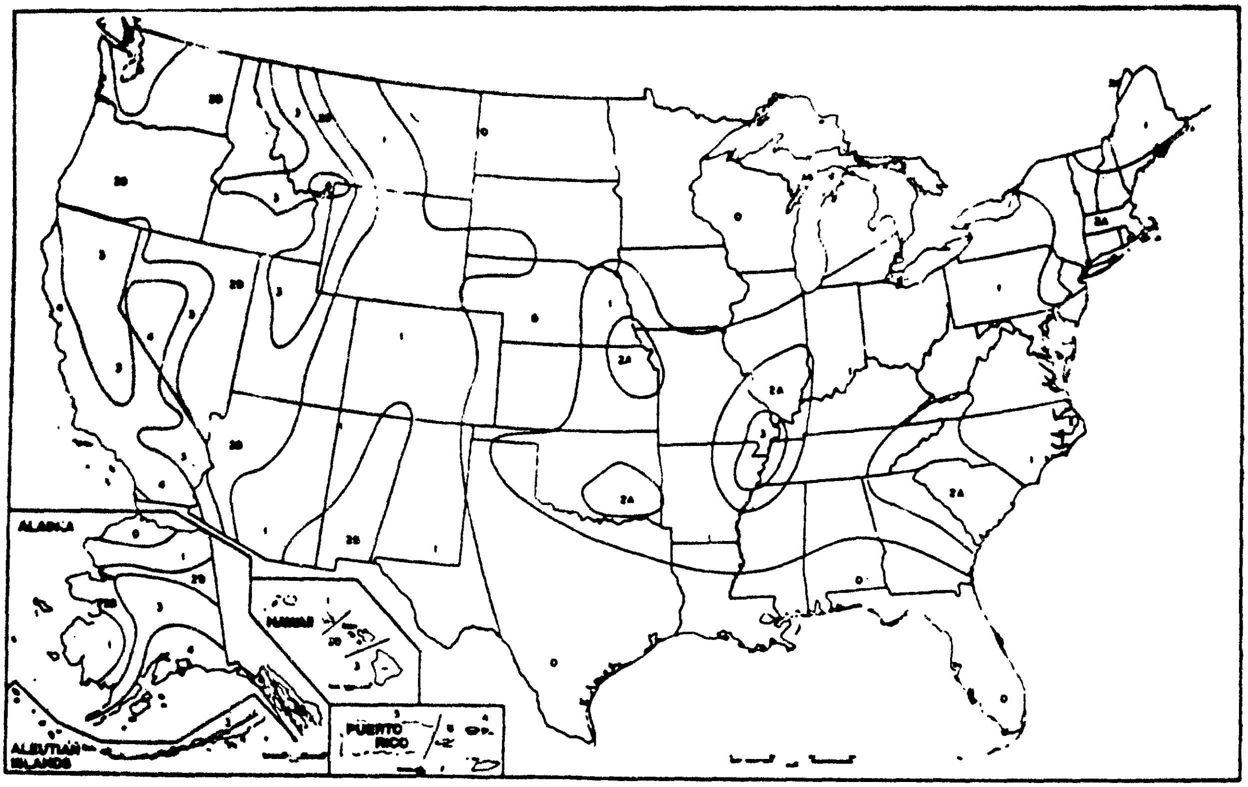
$$\text{Story drift, } \Delta \leq 0.04h/R_w \text{ nor } 0.005h$$
$$\text{where } h = \text{story height.}$$

For buildings 65 ft. or more in height,

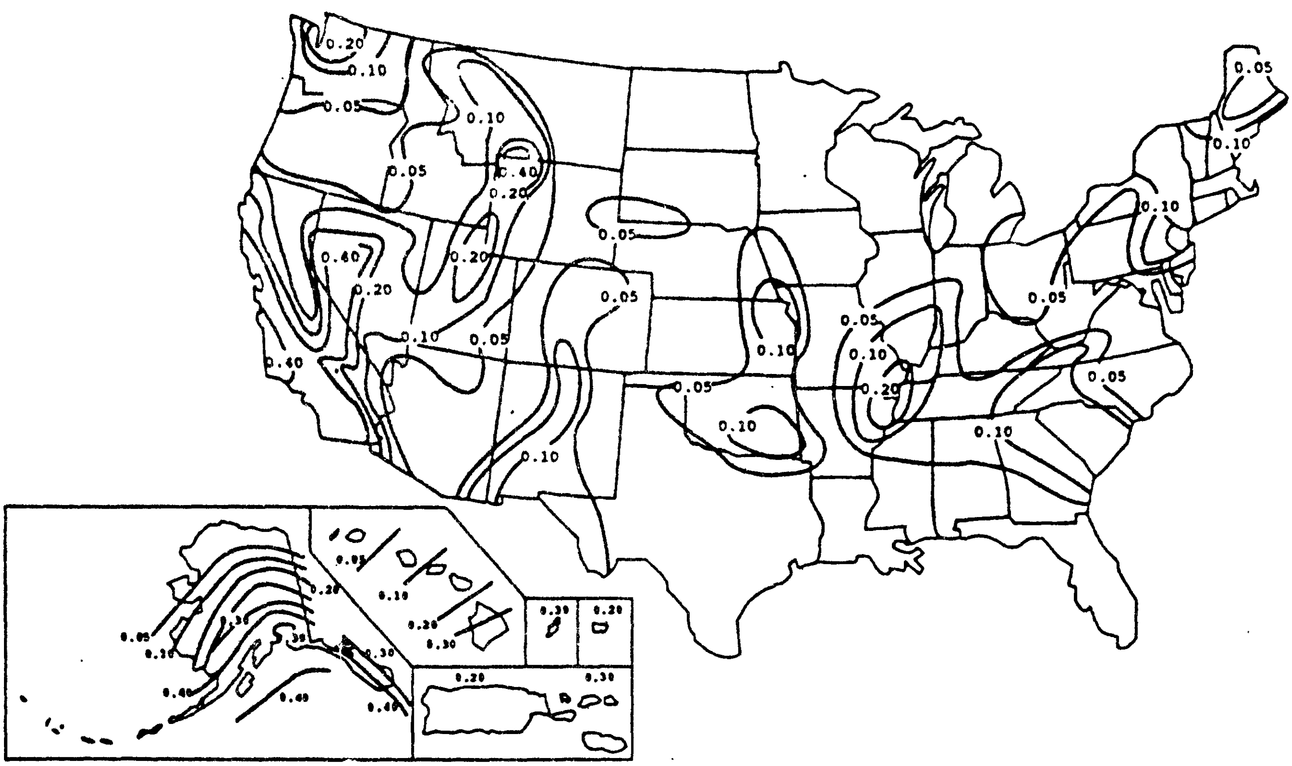
$$\text{Story drift, } \Delta \leq 0.03h/R_w \text{ nor } 0.004h$$

Orthogonal effects

In Seismic Zones 2, 3, and 4, provision shall be made for the effects of earthquake forces acting in a direction other than the principal axes under various circumstances.



Seismic Zone Map - 1988 Uniform Building Code



Contour Map for Coefficient A_a

Contour Map for Effective Peak Acceleration - 1988 NEHRP Provisions

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DRAFT

EXISTING CRITICAL INDUSTRIAL FACILITIES IN TODAY'S SEISMIC DESIGN/EVALUATION CRITERIA ENVIRONMENT

Dr. James Beavers
Martin Mrietta Energy Systems

INTRODUCTION

Background

Critical industrial facilities (CIF's) are those facilities previously defined as (1)[1] "...facilities that, if damaged by a natural phenomenon event, could result in the release of substances harmful to the public or the environment or that could result in what owners consider as unacceptable financial losses." From a seismic design and evaluation point of view, CIF's require more stringent criteria than a general use facility such as an office building, or even hospital, but do not require as stringent criteria as that required for nuclear power plants. From this perspective CIF's can be considered those "in-between" facilities.

Since the seismic vulnerability of existing CIF's began to be seriously addressed, a number of events have occurred that have resulted in a change in attitudes by owners, managers, engineers, operators and the public and its representatives. This change has resulted in the need for a better understanding of the vulnerabilities of CIF's from all aspects of operation including natural phenomena and has resulted in a heightened responsibility by all to provide safe operating facilities to protect the public, employees and the environment. Although a number of events might be cited the following six say it all:

[1]Numbers in parenthesis refer to references

1) The Three Mile Island (TMI) nuclear power plant accident of March 28, 1979 (2) that made headlines for days around the world; 2) the December 3, 1984 toxic chemical release in Bophal, India (3) that resulted in over 2000 deaths and 150,000 injuries; 3) the Mexico City earthquake of September 19, 1985 (4) that resulted in 10,000 deaths; 4) the Challenger disaster of January 28, 1986 (5) in which a simple O-ring resulted in the loss of ship and crew; 5) the Chernoble nuclear power plant accident of April 26, 1986 (6) where acute radiation exposure resulted in 31 deaths and more than 135,000 people were evacuated and 6) the December 3, 1988 Armenian earthquake (7) of magnitude 6.9 that resulted in over 25,000 deaths. In addition to these major historical events the public as a whole has become more aware of the earthquake hazards issues in the United States as a result of educational programs supported by the National Earthquake Hazards Reduction Act of 1977 (8) such as the Southern California Earthquake Preparedness Program [SCEPP] (9), Earthquake Education Center at Charleston, South Carolina (10) and the Earthquake Education Center at Memphis Tennessee (11); a host of other efforts by the Federal Emergency Management Agency (FEMA), U. S. Geological Survey (USGS), National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST)--the four federal agency recipients of the 1977 Act funding; efforts by the Earthquake Engineering Research Institute (EERI), other professional societies and nonprofit groups; individual engineers and scientists; and the continuation of earthquake occurrences in the U. S.

To date there have been no recognized guidelines established for the design and evaluation or retrofit of CIF's. During the 1960's and 1970's most of the focus was being placed on seismic design of general use and nuclear power plant facilities. However, it was not until 1973 that the U. S. Atomic Energy Commission (AEC), now the Nuclear Regulatory Commission (NRC), began publishing design requirements for nuclear power plants (12 and 13, for example) and it was not until 1980 that documentation of seismic design criteria began being published (14, 15, 16) for CIF's.

Following the San Fernando earthquake of 1971 (17) the earthquake engineering profession spent a considerable amount of time and effort developing a comprehensive document for the design of buildings. This effort lasted throughout the 1970's and the results were finally published in 1978 (18) with the results of a follow-up assessment being published in 1979 (19). However, today and in the next two or three decades, the number of new facilities being placed into the total U. S. stock will be trivial compared to that already in place. Thus the real issues of earthquake damage mitigation are not design criteria development or code adoption for new facilities but must be seismic evaluation, assessment and retrofit guidelines and requirements for existing facilities. Although the title of this paper implies that key issues of design criteria are going to be addressed, they will only be addressed in the context that they impact existing facility evaluation. Since design criteria established a major foundation for the development of evaluation criteria and changes in design criteria approaches can have major impacts on evaluation criteria, the words "design criteria" were included in the paper title.

Evaluation Criteria Development

During the late 1970's and early 1980's the lack of understanding of the seismic performance of existing facilities began to be addressed by the engineering profession and guidelines began to be discussed and developed. Because the 1971 San Fernando earthquake resulted in the collapse of a Veteran's hospital built in 1944 and more recently-built structures (17), the federal government and the engineering profession began addressing the needs for the evaluation and upgrade of existing facilities. These efforts resulted in the publication of a number of recommended guidelines for the evaluation of buildings (20, 21, 22, 23). Also during the late 1970's the NRC began supporting work for the development of guidelines for the purpose of seismic review of nuclear power plants placed into operation before NRC had established all of its seismic design requirements, one set of recommendations being published in 1978 (24).

During the 1980's the concerns for evaluation and retrofit guidelines heightened and a number of national and international workshops were held (25, 26, 27, 28). In addition a number of papers were presented suggesting simplified methods for assessing the seismic vulnerability of buildings and corresponding retrofit procedures (29). The most recognized set of evaluation guidelines for buildings developed to date are those published by the Applied Technology Council (30) and detailed guidelines are currently being developed (31). However, the main issues addressed in all of these documents, like those developed in the late 1970's, have to do with the evaluation procedures used for general use buildings and do not really address many of the unique features of CIF's.

The first known paper to be published solely for the intent of establishing guidelines for the evaluation of existing CIF's was in 1981 (1) at the first national conference to focus on earthquake engineering issues in the eastern U. S. (32). This paper attempted to use NRC requirements as an upper bound while at the same time developing a set of evaluation guidelines that would result in a best-estimate of the seismic vulnerability of an existing CIF. Recently (33) the U. S. Department of Energy (DOE) has developed what this author believes may be the first recognized set of evaluation guidelines that provide recommended procedures for evaluation and retrofit requirements of existing CIF's. The document containing these guidelines is known as "UCRL-15910" (stated UCRL fifteen nine ten) and is also applicable for design of new facilities. Although UCRL-15910 is still in draft form and a workshop is scheduled to be conducted in May, 1989 the guidelines are being followed by a number of DOE sites--their operating subcontractors and Architect-Engineers. These guidelines which are also a mix of new design procedures and evaluation criteria will be discussed in more detail below.

In the past when the design of new or evaluation of existing CIF's became an issue there was a tendency by some to recommend that the requirements for the design of nuclear power plants should be followed. In some cases this tendency has been especially strong for facilities such as nonreactor nuclear facilities even though the major hazard of such facilities may be toxic chemical rather than radiation release. This trend was especially true in the late 1970's and early 1980's because the "earthquake industry" (the term "earthquake industry" herein refers to the study of earthquakes to include geophysics, seismology, geology, engineering, preparedness, etc.) had developed and seemed to understand the requirements for design of general use facilities, i.e. ATC 3-06 (18) and building codes (34) and had developed the regulatory requirements for nuclear power plants (12 and 13) and the Standard Review Plan (35). However, except for a few isolatec cases (1, 14, 15 and 16) nothing had been developed, and there seemed to be a lack of understanding, for those "in between" facilities-- those that definitely should require more seismic design/evaluation rigor than used for general use facilities, but definitely should not be as rigorous as those for nuclear power plants. Therefore what was believed needed by this author and others was a balanced approach that utilized portions of both the requirements for nuclear power and general use facilities depending upon whether the CIF was new or existing, what the life expectancy was and what the facility hazards were--a balanced risk approach (36 for example).

The purpose of this paper is to discuss some of the key issues in the seismic evaluation and retrofit of existing CIF's, evaluation guidelines that have been developed, the approach to some evaluations that have been conducted, the potential cost implications of retrofit where retrofit is needed and the impact of new design criteria on such facilities. It should also be pointed out that although seismic evaluation of existing nuclear power plants has been conducted (37) because of the changing criteria over the years, seismic evaluation of such plants will be one of the major focuses of the NRC in the future since many of the U. S. plants have or are reaching the end of their planned life cycle (40 years in most cases) and the current trend is to extend plant lives (38). Many of the developments that result from these efforts will be applicable to existing CIF's.

STATE OF EVALUATION AND RETROFIT

Existing CIF's

Many of today's CIF's were designed and constructed before seismic design of such facilities became a recognized requirement. It has been only recently that states and municipalities in the U. S., other than California, have adopted seismic provisions in their building codes, and those provisions primarily apply to general use facilities. The adoption of seismic codes and the implementation of seismic design for CIF's have been particularly acute problems in the eastern U. S. where, except for the case of nuclear power, the need for seismic design was almost totally ignored because of the perceived seismic hazard being one of "no hazard" (39). As a result, most existing CIF's will not meet today's seismic design requirements and in many cases may have very little, if any, lateral force resistance capability. What lateral force resistance capability they may have will exist as a result of design for wind or crane loads. In general, in the eastern U. S. those CIF's built in the years prior to 1960 will have no seismic design incorporated. Those designed and constructed in the 1960's and 1970's may or may not have seismic design and those designed and constructed in the 1980's will be more likely to have some seismic design. It was not until 1988 that the Southern Building Code Congress International adopted seismic design requirements in their Standard Building Code (40) although such requirements had been in an appendix for many years.

Purpose of Evaluation and Retrofit

Most of the experience that the engineering profession has today with developing design codes or evaluation guidelines has been based solely on life safety for general use facilities. The main issue being the protection of occupants from collapsing structural or architectural features. Life safety has been the basis for the City of Los Angeles ordinances (41) for retrofiting unreinforced masonry buildings. It is interesting to note that in the Whittier Narrows earthquake of October 1, 1987 (42) those unreinforced masonry buildings that had been upgraded according to the required ordinance at a cost of $6.00 to $10.00 per square foot (43) did their job--they provided life safety. However a large number of those upgraded facilities suffered enough damage from the earthquake that they were not repairable and had to be torn down.

In comparison to general use buildings the basis for evaluation and retrofit of CIF's is much more far reaching. In general terms the basis is the protection of the public, employees and the environment. Because of their nature, e.g.
a toxic chemical plant, this basis or criterion will require continued operation and/or safe shutdown capability during and/or following an earthquake event. Thus the evaluation and ensuing retrofit automatically becomes more extensive because failure of a simple O-ring, as in the case of the "Challenger", could result in unacceptable operation interruption or failure of safe shutdown capability. From these generic statements it would appear that the basis for evaluation and retrofit of CIF's are the same as those for existing nuclear power plants and in a sense they are. However, it is the degree of evaluation and retrofit that distinguishes the differences based upon the hazards involved and consequences of failure as noted above and discussed more thoroughly below.

Evaluation and Retrofit Issues

A number of issues must be addressed when examining the seismic vulnerability of a CIF and the resulting retrofit, if retrofit is required. Many of these issues would also be addressed if a comprehensive seismic vulnerability study were to be conducted for an important general use facility such as a hospital, and of course most all of these issues would be addressed if the study was being conducted for a nuclear power plant. Table 1 presents a listing of some of the key issues that most be addressed when developing seismic evaluation guidelines or design criteria for a CIF. Table 2 presents a listing of those issues that must be resolved when examining the retrofit requirements. Discussions on what this author feels are some of the major issues listed in these tables as they apply to existing CIF's are presented in later sections of this paper.

EXISTING FACILITY VS SEISMIC HAZARD

The Decision to Evaluate

When an existing CIF is encountered the first step is to determine whether a seismic evaluation is required. If it is determined that the CIF was not designed and constructed for seismic loads the first step toward conducting an evaluation has occurred. However, since the Uniform Building Code (44), for example, does not require retrofit of existing facilities, even when modifications or additions are being made, an evaluation most likely will not occur unless there is continued economic viability concern or issues concerning the potential threat to the employees, public or environment have been raised. In the eastern U. S. where the seismic hazard is relatively low, and as noted earlier may be perceived by

TABLE 1

Seismic Evaluation Guideline Issues for Existing CIF's

Issue No.	Issue	Brief Description
1.	Seismic Hazard	How Is The Seismic Hazard Defined--Probe/Deterministic
2.	Site/Geotechnical Characterization	Can Seismic Forces be Amplified, Soil-Structure Interaction, Liquefaction
3.	As-Built Condition	Drawings Must Match Field Conditions, Corrosion Effects Must be Considered
4.	The Decision/Facility Hazard	On and Off Site Consequences of Failure and Economic Consequences
5.	Classification Requirements	What is Important to Maintain Safety What is Important to Maintain Operations
6.	Seismic Input	Response Spectrum, Time-Histories, etc.
7.	Analytical Procedures	Modeling, Damping, Elastic and Inelastic Methods
8.	Structural Capacity	Inherent Member Strength, Capacity Factors, Ductility Characteristics
9.	Qualification Requirements	Experience Data, Analysis, Testing
10.	Quality Assurance	Computer Codes, As-Built Conditions
11.	Probe Risk Analysis	Experience Data Base, Analytical Rigor
12.	Levels of Evaluation	

TABLE 2

Seismic Retrofit Issues for Existing CIF's

Issue No.	Issue	Brief Description
1.	Worst Case Event	On and Off Site Consequences of Failure and Economic Consequences
2.	Levels of Retrofit	Consequence vs. Retrofit Costs
3.	Political Climate	Management Decision vs. Overall Issues
4.	Retrofit Alternatives	Operational/Administrative Changes vs. Retrofit
5.	Retrofit Approach	Alternatives Between Retrofit Techniques
6.	Changing Requirements	Base Isolation or Strengthening
7.	Additions/Alterations	
8.	Quality Assurance	
9.	Operational Cost Impact	
10.	Life Expectancy	

many to be even lower, continued economic viability will not usually justify an evaluation and in only the very unusual cases would such an evaluation result in retrofit. Thus, understanding the CIF hazard is the key to the decision making process in conducting or not conducting a seismic evaluation of a CIF, an evaluation which becomes a seismic vulnerability study. To fully understand the levels of hazard and risk that exist for a particular CIF would require a probe risk analysis (PRA). However, to gain an understanding of the degree of seismic evaluation required based on the degree of hazard, a simplified worse case event can be more rapidly assessed. This can be accomplished for a toxic chemical facility, for example, by taking the inventory of a particular area and evaluate a "throw it up in the air" event. Although this may seem very crude and simplistic, if the results show no off-site consequences for such an event then the most sensitive level of concern has gone away. The concerns are then only limited to environmental issues and protection of employees, employees who are trained and have access to safety equipment to mitigate personal exposures. In the case of an environmental insult, many such insults occur as spills and can be cleaned up before there is any chance to have an adverse impact on the public.

The above type of consequence analysis process has resulted in establishing CIF hazard categories that represent the depth and degree of evaluation procedures required and the levels of retrofit that might be required. In the DOE guidelines (33) such facilities would be placed in one of three hazard categories of Important or Low Hazard, Moderate

Hazard and High Hazard as shown in Table 3. It is important to note that the category level of facility hazard cannot be lowered based on engineered safety systems. A high hazard facility is always a high hazard facility while the engineered features make the facility a safe facility to operate.

Seismic Hazard

One of the major issues the earthquake industry has faced in the past has been the establishment of the seismic hazard (Table 1) for a particular site. This has been particularly acute in the eastern U. S. because of the lack of earthquake occurrences and the inability to identify the faulting that has caused historic earthquakes. Although numerous studies have been conducted on the subject (45, 46, 47, 48 for example), significant uncertainty still exists. Figure 1 shows the results of approximately ten different hazard studies conducted over a ten year period for a particular site (Site I)** in the eastern U. S. (49). The results are usually shown as seismic hazard curves in terms of peak ground acceleration vs annual probability of exceedance or return period. As can be seen in Figure 1, at a probability of exceedance level of 1×10^{-3} per year (1,000 year return period) the estimated peak ground acceleration ranges from 0.08 g to 0.33 g. Most of the ten different study groups conducted their work independent of the others. In some cases

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**For the purposes of this paper, examples have been shown in generic form but represent actual cases in the eastern U. S. Details may be obtained from cited references.

TABLE 3
FACILITY-USE CATEGORY GUIDELINES*

Facility-Use Category	Description
Important or Low Hazard Facilities	Facilities which have mission dependent use (e.g.,laboratories, production facilities, and computer centers) and emergency handling or hazard recovery facilities (e.g., hospitals, fire stations).
Moderate Hazard Facilities	Facilities where confinement of contents is necessary for public or employee protection. Examples whould be uranium enrichment plants, or other facilities involving the handling or storage of significant quantities of radioactive or toxic materials.
High Hazard Facilities	Facilities where confinement of contents and public and environment protection are of paramount importance (e.g., facilities handling substantial quantities of in-process plutonium or fuel reprocessing facilities). Facilities in this category represent hazards with potential long term and widespread effects.

*Taken from Reference 33

a study group provided minimum and maximum seismic hazard curve estimates or a "best estimate" with $\pm$ one sigma and for others peak ground acceleration was given with a range on probability of exceedance. Although the uncertainty shown in Figure 1 is not new to those in the field, it is representative of a potentially serious problem for existing CIF's when their seismic resistance capacity limits lie near or within the range of seismic hazard uncertainty.

More recent work has been completed by the Electric Power Research Institute (EPRI), (50) and Lawrence Livermore National Laboratory (51) for developing new seismic hazard estimation methodologies, with the use of expert opinion to alleviate many of the seismic hazard uncertainties for the eastern U. S. It is the opinion of this author that these two methodologies when used properly will give reasonably consistent estimates of the seismic hazard and represent state-of-the-art. If differences exist between the two methodologies for a particular site the methodologies can be equally weighed and those differences can be worked out. It is also the opinion of this author that unless a surprising amount of new knowledge or data is obtained for the eastern U. S. very little, if any, "real" improvement will occur in the estimation for seismic hazards in the East above and beyond these existing methodologies for many years to come. The earthquake industry may already be "splitting the hair" with the appearance of accuracy when the geological and historical data do not support such accuracy. In reality the eastern U.S. is going to have to experience a number of major earthquakes for significant improvements in seismic hazard estimation to occur.

Existing CIF/Seismic Hazard Conflicts

As noted above the importance of understanding the seismic hazard at the site of an existing CIF is extremely important. For example, Figure 2 shows the seismic response characteristics of a CIF (CIF-I***) designed and constructed in the eastern U. S. in the late 1940's and early 1950's (52) without consideration for earthquake loads. As a result, yielding of various members occurs at the very low ground acceleration level of 0.05 g and the structure has been shown to be at 100% damage (unrepairable) at about 0.3 g. Although yielding of some structural members occurs at 0.05 g, it is believed (52) that CIF-I will either continue operating or safely shut down at an earthquake acceleration of 0.20 g without requiring major retrofit. However the two real questions are: 1) What is the "real" seismic hazard? and 2) What is the "real" seismic capacity of the CIF? Unfortunately, for the site where CIF-I was constructed, the difference between an acceptable seismic hazard of 0.20 g versus an unacceptable seismic hazard of 0.30 g is well within the uncertainty bound demonstrated in Figure 1. To add additional conservatism in the seismic hazard estimates by using 0.30 g rather than 0.20 g will not have a major impact on the design and construction of a new facility but it will have a tremendous impact on CIF-I. To upgrade CIF-I to maintain the described performance of continued operation or safe shutdown at 0.20 g, the cost impact represented about a $5 million

***See footnote, page 14.

capital investment. This investment provided for upgrading a process piping system "weak link" and did not include structural upgrade (52). At 0.20 g structural damage will occur as a result of permanent deformation, bracing failures, banging (impact) effects and architectural damage and repair is quite feasible if such an event occurred. Unfortunately, since one building system of CIF-I, for example, incompasses an area of over twenty-five acres involving thirty independent structural units, upgrading to minimize damage at 0.30 g could result in a capital investment at CIF-I in the hundreds of millions. Thus, this "real life" seismic vulnerability example points out the need to fully understand the seismic hazard at a particular site and the elastic and inelastic response of the CIF's at that site.

Facility Hazard vs Seismic Hazard

As noted above a major key to the decision to evaluate and/or retrofit an existing CIF is dependent upon the particular CIF hazards. Therefore it is extremely important to understand the CIF hazards. These hazards can be in the form of toxic chemicals, explosives and/or radiation. Figure 3, Curve I, shows the relationship between an "Exposure Index" (EI) and the seismic damage of a typical CIF (1). The EI is used herein as a qualitative measure of the dose the public, an employee or the environment might be subjected to. At what can be considered 100% damage the EI will be at its peak. However depending upon the characteristics of a particular CIF the EI could peak at a much lower level of damage as shown in Curve II. Of course it is important to understand the facility hazards for other reasons than seismic hazards. There are a number of other initiating events that could cause the release of hazardous materials to the public and the environment which have led some owners/operators to conduct PRA's. (53)

The main purpose in understanding the seismic hazard and the CIF hazard is to minimize the EI to accceptable levels to protect the employees, public and the environment in the event of a major earthquake. In simplified form the higher the seismic hazard the greater the risk or the higher the CIF hazard (potential for greater EI) the greater the risk. In either case the degree of evaluation and the degree of retrofit are both functions of the two hazards.

EVALUATION/DESIGN GUIDELINES

The Basis

When examining an existing CIF for seismic capacity versus seismic demand the main purpose is to provide a safe facility. Most of the CIF's that were not originally designed for earthquake loads will be shown to be deficient when compared to the design requirements of today. Even if there are no existing state or municipality seismic codes that apply where a CIF is located it will still be deficient based on state-of-the-art. However to upgrade an existing facility can result in significant capital outlays depending on how safe is safe enough.

The guidelines discussed and recommended herein are based on the following premise: "An existing CIF does not have to meet today's design criteria to the letter of the law, nor do the evaluation guidelines/requirements need be as conservative as those design criteria developed for a new CIF of the same hazard level as long as the general intent of current design criteria are met and that the public nor the environment are subject to undue risks." This premise assumes that for an existing facility a higher level of risk is acceptable when comparing the increased cost to reduce the risk of an existing facility versus a new facility. Obviously, each case of an existing CIF must be weighed on its own merit, the hazards involved and its remaining life, and such technical and management decisions tend to be much more complex than for a new CIF.

Evaluation/Design Procedures

For the seismic design of a new CIF the analytical approach will take on the characteristics of some form of dynamic analysis utilizing earthquake time histories or response spectra as input. In the past, the modeling of structures and the corresponding analyses were usually based on two dimensional models with response spectrum input. However with the changes in computer technology the trend now is to develop the three dimensional model at the outset with inputs being in the form of time-history records whose response spectra envelope a given design spectrum. These more sophisticated analysis techniques are being carried over into the evaluation of existing facilities.

In previous assessments for the evaluation of existing CIF's this author, with others (1, 49 and 52), made a number of recommendations. In these cases it should be pointed out that the purpose was to conduct vulnerability studies and was not intended to be used to evaluate a CIF against specific criteria. Although not inclusive, the following recommendations represent what this author considered at the time and today, the most pertinent:

1. One of the first recommendations made was that the seismic input data for the evaluation/analysis should be based on an estimate of the effective PGA (EPGA) because PGA values are just that, "peak", are not representative of what structures will respond to and could easily result in a more conservative/expensive retrofit than necessary.

2. The as-built condition of the existing CIF must be determined and current conditions, especially in a corrosive environment, verified. (Even for new facilities it is amazing how completed construction will differ from certified for construction (CFC) drawings.

3. The in-place material strengths should be determined to define seismic capacity since it is known that in-place strength is usually greater than the design strength called out on the CFC drawings. For example, in

many cases the concrete mix used for a specified strength pour will actually be a higher strength mix based on the supplier's added conservatism, and concrete also strengthens with age. In the case of steel it has been shown (54) that A-36 steel has a median yield strength of 42 ksi instead of 36 ksi (17 percent greater).

4. A mean spectrum shape was recommended to be used as being more realistic in the evaluation rather than the mean plus one-sigma which has been the standard in design of nuclear power plants.

5. Existing live loads should only be used in the evaluation unless there are specific plans to increase the existing live loads some specified amount. Design live loads should never be used in an evaluation since they would add unnecessary conservatism.

6. Although not considered a specific recommendation the inelastic capability, ductility of members and connections, and changes in damping ratio with stress were stressed as key factors in understanding the vulnerability of CIF's as discussed below.

Judgement/Experimental Issues

As noted above in the example of CIF-I, yielding of some structural members occurs at the relative low EPGA of 0.05 g. For this particular facility and following the draft DOE criteria (33), using a reasonably conservative approach, it can be determined that a new CIF facility located at the same site should be designed for a PGA of 0.45 g. This situation brings up two important questions: 1) Is it necessary to upgrade and 2) If so, how much upgrading and at what cost? Thus a dilemma rapidly appears of an existing CIF whose structural members began yielding at 0.05 g while new state-of-the-art design criteria requires that a new CIF, with the same facility hazards, at the same site be designed for 0.45 g. Although an inventory analysis of CIF's has not been conducted throughout the U. S. this situation could be typical of a number of CIF's in the eastern U. S. and possibly some older ones in the western U. S. Thus, it is extremely important to fully evaluate the seismic vulnerability of such facilities and determine what the seismic response of such facilities are throughout a range of EPGA's from the onset of yielding to the possibility of collapse, or at least to a conservative seismic hazard level (EPGA) for a particular seismic zone.

Unfortunately in cases like those mentioned above the typical, simple linear-elastic dynamic analysis almost becomes of little value. What is needed is a well developed inelastic analysis with strain hardening characteristics, multiple collapse mechanisms, variable damping capability, variable model change capability, etc. Because such analytical techniques are generally only available at best in the laboratory or for the most simple of structures, engineering judgement must be relied upon using the linear-elastic analysis and/or very simplified inelastic analyses as an aid. Unfortunately complex existing facilities that have been around for thirty to forty years are usually not simple to model and when modeled do not remain elastic as noted above for determining the seismic capability of structures, equipment and piping systems. During the past decade a tremendous amount of work has been conducted on the use of engineering judgement and experience for determining the seismic capability of equipment and piping systems, especially by the Seismic Qualification Utility Group [SQUG], (38, 55 and 56). This effort has resulted in the development of data bases for the performance of equipment and piping systems during experimental qualification testing and, most important, the performance of such systems in actual earthquakes around the world. This approach has been extremely useful for determining the vulnerability of equipment and process piping systems in existing CIF's. However a ready data base is not available for the varied types of complex structures that exist is such facilities.

To date the only experimental test facility available to the engineer for major structures has been the actual event of an earthquake that resulted in various levels of damage to structures such as the Mexico City earthquake of 1985 (4) and the Armenian earthquake of 1988 (7). Obviously, it would be advantageous to test an existing CIF on a large shake table but the practicality forbids it. Thus the engineer is still left with the difficult task of determining the seismic vulnerability of a complex CIF using simple analysis, engineering judgement and experience. The issues that engineers and managers face in such circumstances are further discussed below.

DOE Guidelines

As discussed above the DOE has developed a draft set of natural phenomena design and evaluation guidelines known as UCRL-15910 for its facilities throughout the U. S. (33). These guidelines were prepared by a group of consultants with a DOE appointed Natural Phenomena Committee to recommend and review. Although the document states that the intent is for the use of evaluating existing facilities, this author believes that many of the guidelines shall lean toward the design of new facilities. However, this author still believes that UCRL-15910 is a major step toward developing seismic evaluation criteria for existing CIF's. The general purpose of UCRL-15910 was to develop design and evaluation guidelines for CIF's and to establish a consistent approach to be used by all DOE sites throughout the U. S. As stated earlier there has been a need to develop design criteria for CIF's , those "in-between" facilities. In addition, there has been a serious need for the development of evaluation guidelines for existing CIF's because of the large stock of such facilities in the U. S. and the DOE system.

When using the UCRL-15910 approach to evaluate an existing CIF, a somewhat different and more simplistic approach is taken than the vulnerability assessment approach discussed above. In UCRL-15910 a set of seismic resistant evaluation requirements have been established that an existing CIF should meet. Thus a vulnerability study where technical/management decisions must be made on the acceptable levels of risk are not required. Acceptable levels of risk have essentially been established in UCRL-15910 and if an existing CIF does not meet those requirements, retrofit is required.

Some of the concerns that were expressed above for a vulnerability study such as the seismic hazard, amount of ductility, types of analyses, can be alleviated if such requirements are acceptable. However from the outset it is expected that many existing CIF's, such as the CIF-I example, will not meet those requirements without significan capital outlays for retrofit costs. Thus the reviewers of a particular facility began to question the amount of conservatism in such a document as UCRL-15910 and how applicable is it to a particular existing CIF (57).

Many of the key elements of a vulnerability study discussed in the above sections were discussed and debated by the DOE Natural Phenomena Committee and the principal authors of UCRL-15910. Some key recommendations or requirements of UCRL-15910 and supported by this author as is evident by the discussions above are: 1) Mean response spectrum shapes should be used when evaluating existing CIF's and 2) A higher level of risk is acceptable for an existing CIF if the facility cannot meet the requirements of the first level of risk recommendation (i.e., first evaluate the CIF for a $1x10^{-3}$ per year expected threshold ground acceleration probability of exceedance and if that cannot be met examine a $2x10^{-3}$ per year event). If the existing CIF meets the higher risk requirements then the facility is generally acceptable.

In UCRL-15910 considerable discussion also occurs about the remaining life of an existing facility being a consideration, however, no guidelines for such consideration have been established. This remaining life of an existing CIF issue is discussed more thoroughly below.

A major advantage of using a seismic design/evaluation approach as presented in UCRL-15910 is that the authors tried to use current available technology as much as possible rather than developing new procedures. As a result UCRL-15910 has heavy emphasis on the 1988 edition of the UBC (44) and the Army, Navy and Air Force "Seismic Design for Buildings" manual (58).

Following the UCRL-15910 workshop being scheduled for May, 1989 it is hoped that current conflicting issues can be resolved, suggested modifications to existing methods improved and the document issued in mid-1989. If these goals are accomplished it is believed that UCRL-15910 will represent the state-of-the-art in the design and evaluation of existing CIF's.

NRC Approach

Today the NRC does not have an established set of guidelines for the evaluation and retrofit of existing nuclear power plants. However the NRC has done a tremendous amount of work in this area over the last fifteen years and especially the last ten. Although the NRC's approach is somewhat different than the vulnerability/risk assessment approach and the DOE approach discussed above, there are many similarities. The NRC's main concern is twofold: 1) Can a commercial nuclear power reactor safely shut down at the designated safe shutdown earthquake (SSE) and 2) what are the seismi margins of power reactors if the SSE is exceeded. The main difference between the NRC approach, the vulnerability/risk assessment approach and the DOE approach discussed above is the level of conservatism, detailed investigation and documentation that is required to assure that such conservatism exists for nuclear power plants. This additional conservatism and assurance is being required because of the increased level of consequence should a commercial nuclear power plant fail to perform its safety functions.

The work that has been done in the support of seismic design and evaluation of nuclear power plants used properly is directly transferrable to CIF's. The SQUG database mentioned earlier is quite applicable for CIF's, however, the more rigorous procedures specified by NRC need not be followed and more liberties can be taken when determining the applicability of a database item comparability with a specific piece of equipment.

Because many of the existing commercial nuclear power plants are now reaching their originally scheduled useful life the trend by many utilities in the U. S. is to get the useful life extended. As a result, in the future NRC will be placing a greater emphasis on the evaluation of older facilities. Much of what will be learned, when modified accordingly, will be applicable to CIF's.

<u>Expert Opinion Issues</u>

The use of expert opinion has been used extensively in the determination of the seismic hazard for a particular site (50, 51, 59 and 60). When conducting a vulnerability study for an existing CIF the use of expert opinion can also be quite useful. This is especially true for the older, more complex CIF's. One of the major weakness of the "earthquake industry" is the inability to understand the performance of a structure during an earthquake following the exceedance of general yield to collapse. Thus, assembling an expert panel to review elastic and inelastic analytical results, material properties, structural configuration can be extremely valuable. For a more deterministic approach as is specified in UCRL-15910 the use of expert opinion may not be quite so beneficial since actual requirements are specified.

Many issues remain to be solved concerning structural response during earthquakes. The real opportunity to study such performance is following the occurrence of damaging earthquakes. Much has been learned about the performance of structures in the past (4, 17, 29, 42 for example) and more will be learned in the future (7). However it is the author's opinion that the use of expert opinion is going to be a crucial step in the vulnerability risk assessment of existing CIF's that exhibit many of the characteristic of the CIF-I example for some time to come.

MANAGEMENT DECISIONS

Basis for Decision

The key management decision in the evaluation and retrofit of an existing CIF, such as CIF-I, is to retrofit or not to retrofit. This decision must be based on a number of issues, some quantitative and some qualitative. The most important issues will be: 1) Seismic hazard, real vs. perceived; 2) CIF hazard, real vs. perceived; 3) remaining life of facility; 4) worst case scenario consequences; 5) political environment; 6) economic risk; 7) industry standards; 8) cultural environment; 9) maintenance and operating record standards; and 10) public perception. Of these issues, one will usually be the controlling issue. In some cases it has been the real and perceived seismic hazard, the Diablo Canyon nuclear power plant (61), for example. In others the controlling issue may be more of a combination of political and cultural environment such as the High Flux Isotope Reactor (62). Regardless of which factor may be controlling retrofit decisions are usually made when only one or two are the driving forces. Even so such decisions are not simple when a large capital investment is involved unless there is a clear understanding of the return on investment. In the case of upgrade for the production of new products with a tangible return on investment the decisions may relatively easy. However, for the intangible such as retrofiting to upgrade for a seismic event that may or may not happen is difficult.

The Real Decision Maker

Because seismic issues are new to many CIF managers in the U. S., especially the eastern U. S., and because managers are faced with many decisions on a daily basis, a manger does not usually have the time to fully understand the implication of a "to retrofit or not to retrofit decision." In most cases it is difficult for the earthquake engineer to transfer the understanding of a seismic hazard curve other than the return period vs acceleration concept. PRA's have been used extensively in the nuclear power field and are beginning to be used in industry. However, in the past, PRA's were used to show that a certain risk was acceptable by having $1x10^{-6}$ or less per year risk values.

The uncertainties with all of the decision influencing issues discussed above and the technical uniqueness and implication of each, often result in the "real decision maker' being the engineers and scientists who understand the various caveats of each influencing issue. The manager only approves the decision.

Life of a Facility

One influencing issue that has not been discussed yet and has not been accepted by the "earthquake industry" is the "life of a facility" concept. This concept is particular acute the case of an existing facility that may have a remaining life of only a few years. The question or decision making process becomes: Should large capital outlays be made to retrofit a CIF to meet a certain level of earthquake hazard when the CIF has a relatively short remaining life.

It has been shown (45 and 46) that earthquakes occur at a frequency that can be represented by the Poission distribution. It is also recognized that short life facilities have less exposure time than longer life facilities. IF two identical CIF's in both seismic hazard and facility hazard were being constructed both should be designed to the same earthquake level to maintain a certain level of risk over the life of the facility. If such a risk represented a 5 percent probability of earthquake threshold level of exceedance over the life of the facilities and the life for both was 50 years, the per year risk level would be $1x10^{-3}$. Thus the threshold acceleration level from the seismic hazard curve might be 0.45 g. However, if one of the CIF's life was on 25 years and maintaining the same level of exposure risk, (i.e. 5 percent during the life) the per year risk would be approximately $2x10^{-3}$. From the site seismic hazard curve the threshold acceleration level might be 0.25 g, almost half of that for the 50 year life facility.

The concept just described can be extremely important to existing CIF's because it is the total risk over the life of the facility that should be the main concern of the public, owners and managers. What this can mean to an existing facility is that it does not have to be brought up to the same standards that would be required for a duplicate new facility if the existing facility's remaining life is indeed shorter. Unfortunately, this concept has not been readily accepted in the "earthquake industry" although it is being discussed. For some existing CIF's in the eastern U. S. the adoption of this life/risk concept may mean the difference between jobs and continued operation or no jobs and total shutdown.

CONCLUSIONS

New Developments

Within the issues of seismic hazards and the evaluation and retrofit of CIF's a number of developments are occurring that have helped advance the state-of-the-art. The recent developments (50 and 51) in the area of establishing the seismic hazards for sights in the eastern U. S. have been outstanding. The work that has been done by SQUG (55) and its offshoots has simplified the qualification requirements of equipment and placed a more realistic emphasis on equipment performance during earthquakes. The seismic margins program (54) has allowed for a better understanding of material strengths.

A development that is currently ongoing is defining the seismic hazard in terms other than PGA or EPGA. For example, work is being done now toward developing response spectra to be more representative of earthquakes in the eastern U. S. These response spectra are likely to be higher zero period accelerations with higher frequency content and lower, low frequency content. Work is also continuing on aging effects, primarily in the nuclear power field and may have great benefit in understanding the expected performance of CIF's.

Work is also being done to more fully understand the consequences of accidents and how accidents happen. Toxic chemical plume studies are being conducted and methods are being developed for better input into PRA's.

Future Needs

The development studies mentioned above must continue. However there are a number of specific needs that must be accomplished to provide the "earthquake industry" with the knowledge needed for understanding the vulnerability of existing CIF's to major earthquakes. More reconnaissance studies must be conducted of post earthquake disasters. More research must be conducted on the ultimate capacity of materials, especially on the various kinds of masonry materials throughout the U. S. The characterization of earthquake forces must improve. The effects of aging must be understood. Larger, more capable test facilities must be constructed. The as-built and existing conditions of all CIF's must be documented and kept up-to-date.

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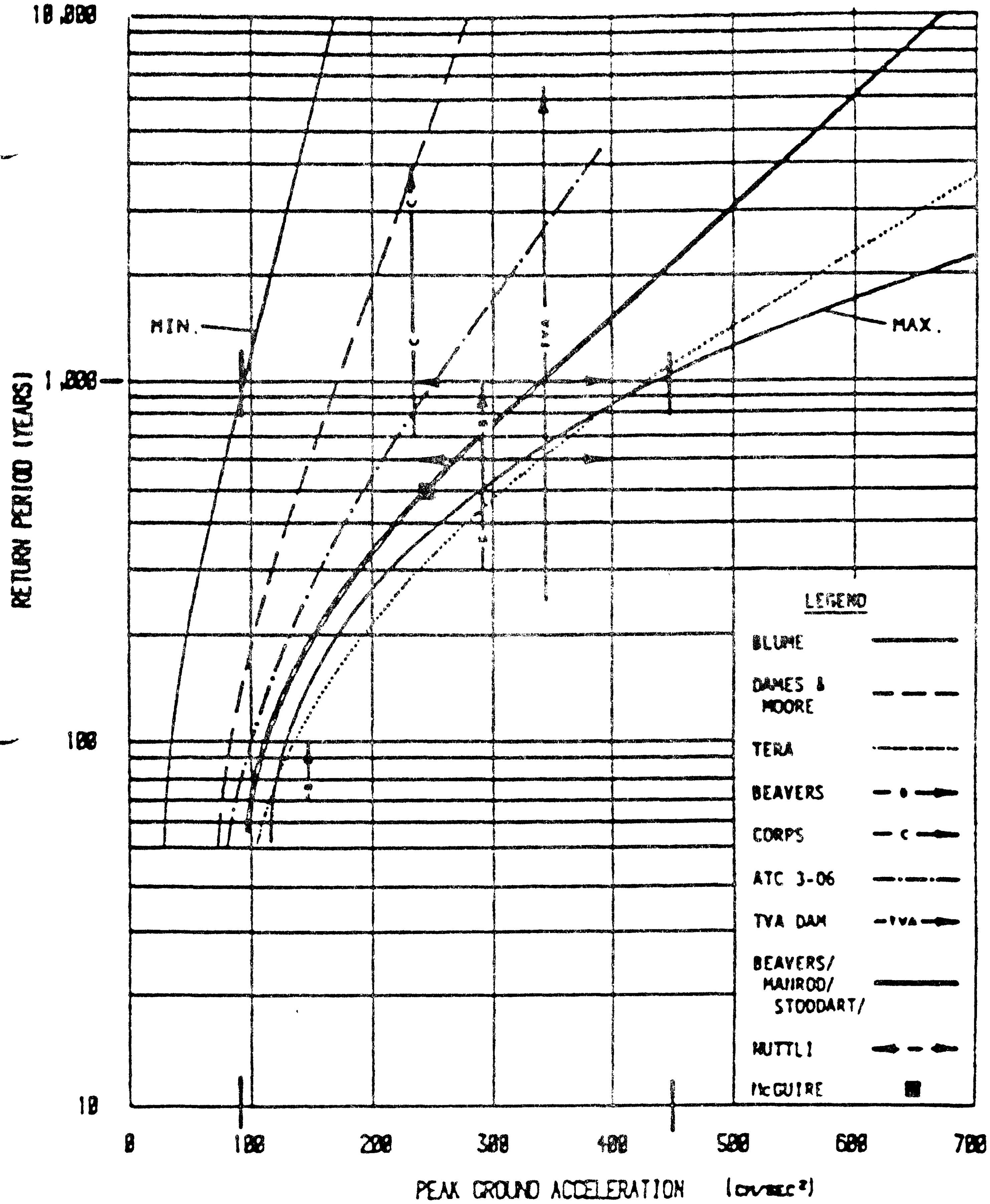


Figure 1. SEISMIC HAZARD CURVES FOR SITE I

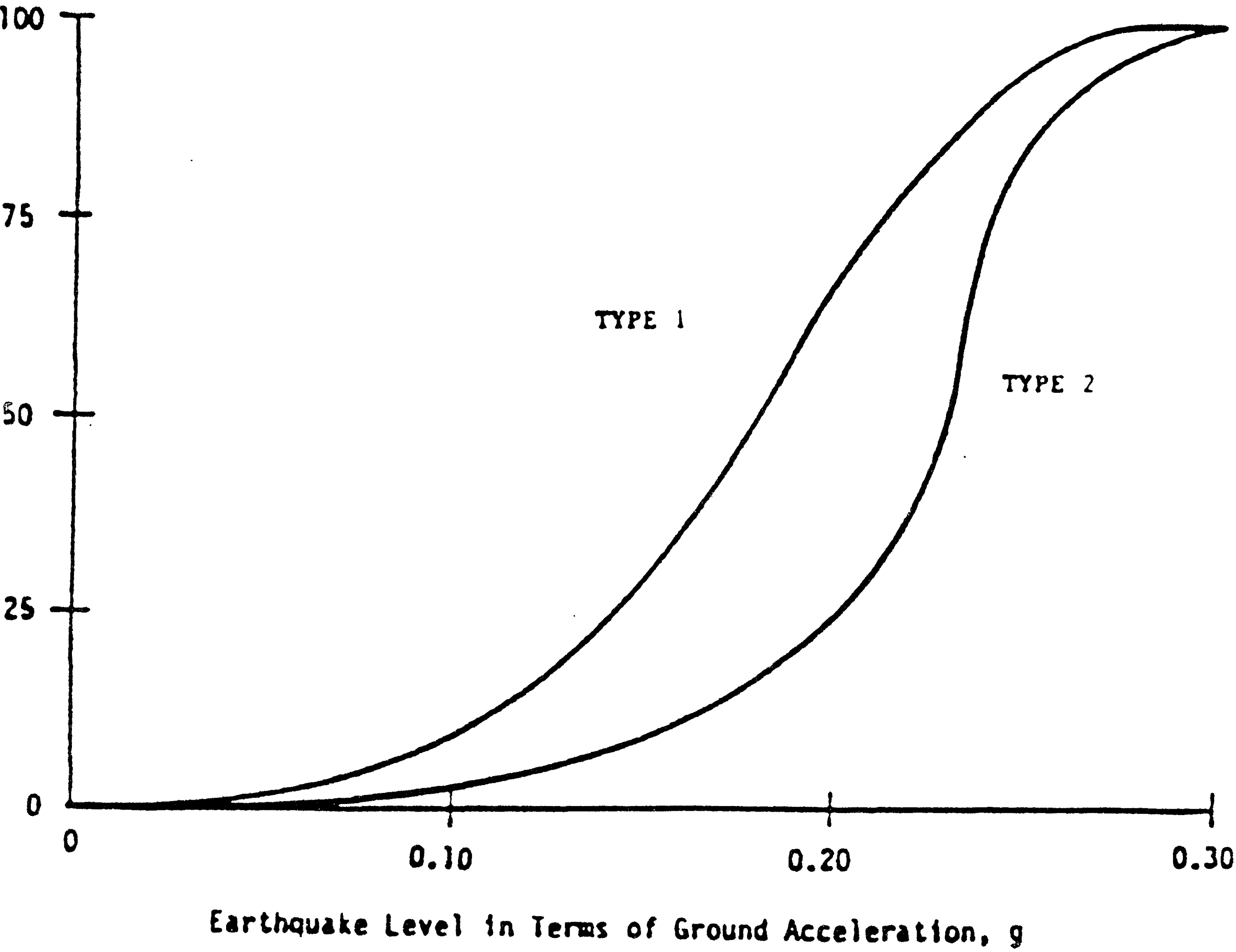


Figure 2. SEISMIC RESPONSE OF CIF-I

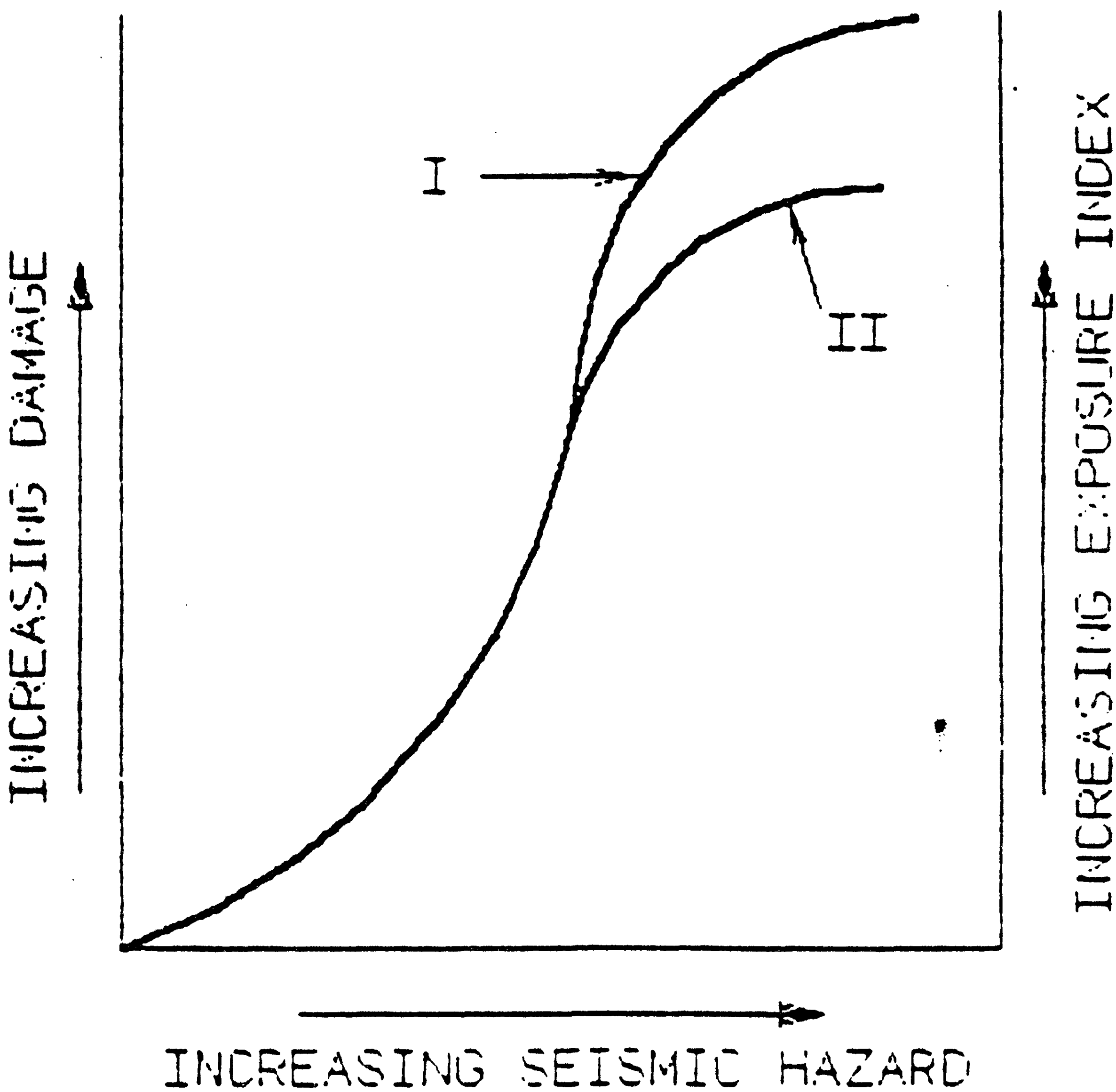


Figure 3. INCREASING SEISMIC HAZARD

EXERCISES TO ILLUSTRATE PROFESSIONAL JUDGMENTS MADE IN SITING, DESIGN, AND CONSTRUCTION

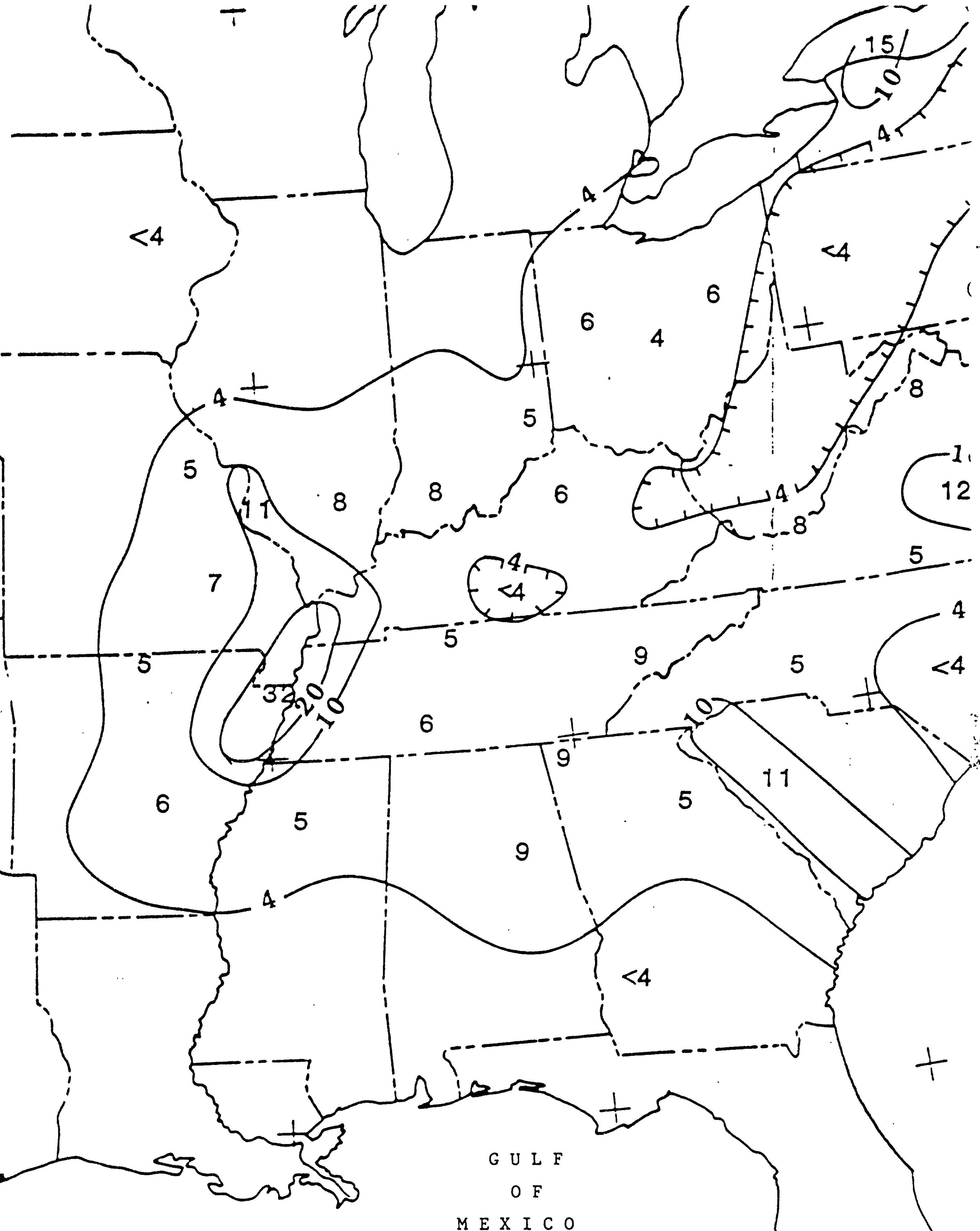
1. Response Spectra
2. Ground Amplification
3. Liquefaction Potential
4. Simplicity and Symmetry of Buildings
5. Design and Construction of Earthquake-Resistant Buildings

Question 1: Maps of the probabilistic ground-shaking hazard in terms of peak horizontal bedrock acceleration (Figure 1) and velocity (Figure 2) are illustrated below.

A. Use these maps to determine the values of ground shaking for:

Memphis:	Acceleration ______	Velocity ______
Little Rock:	Acceleration ______	Velocity ______
Paducah:	Acceleration ______	Velocity ______
Popular Bluff:	Acceleration ______	Velocity ______
Carbondale:	Acceleration ______	Velocity ______
Evansville:	Acceleration ______	Velocity ______
Jackson:	Acceleration ______	Velocity ______
St. Louis:	Acceleration ______	Velocity ______
Your City:	Acceleration ______	Velocity ______

B. For each city, construct a smooth 5-percent damped response spectrum on tripartite logarithmic paper. Refer to Figure 3 for a definition of the response spectrum and Figure 4 for guidance.



1.--Map of peak horizontal bedrock acceleration expected in a 50-year
re time with a 90 percent probability of nonexceedance (from Algermissen
hers, 1982). Values are given in percent of gravity.

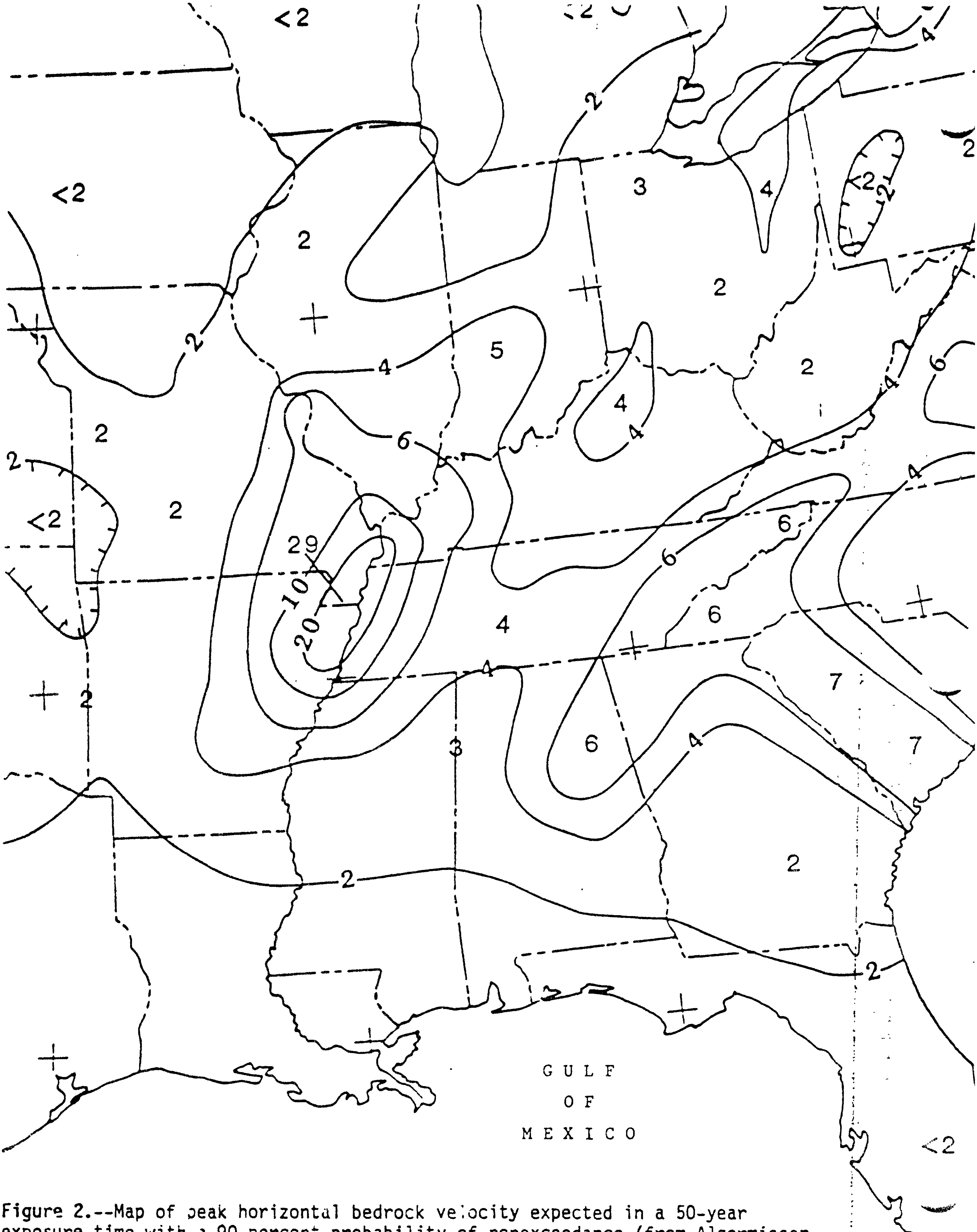


Figure 2.--Map of peak horizontal bedrock velocity expected in a 50-year exposure time with a 90 percent probability of nonexceedance (from Algermissen and others, 1982). Values are given in centimeters/seconds.

GROUND MOTION AND THE RESPONSE SPECTRUM

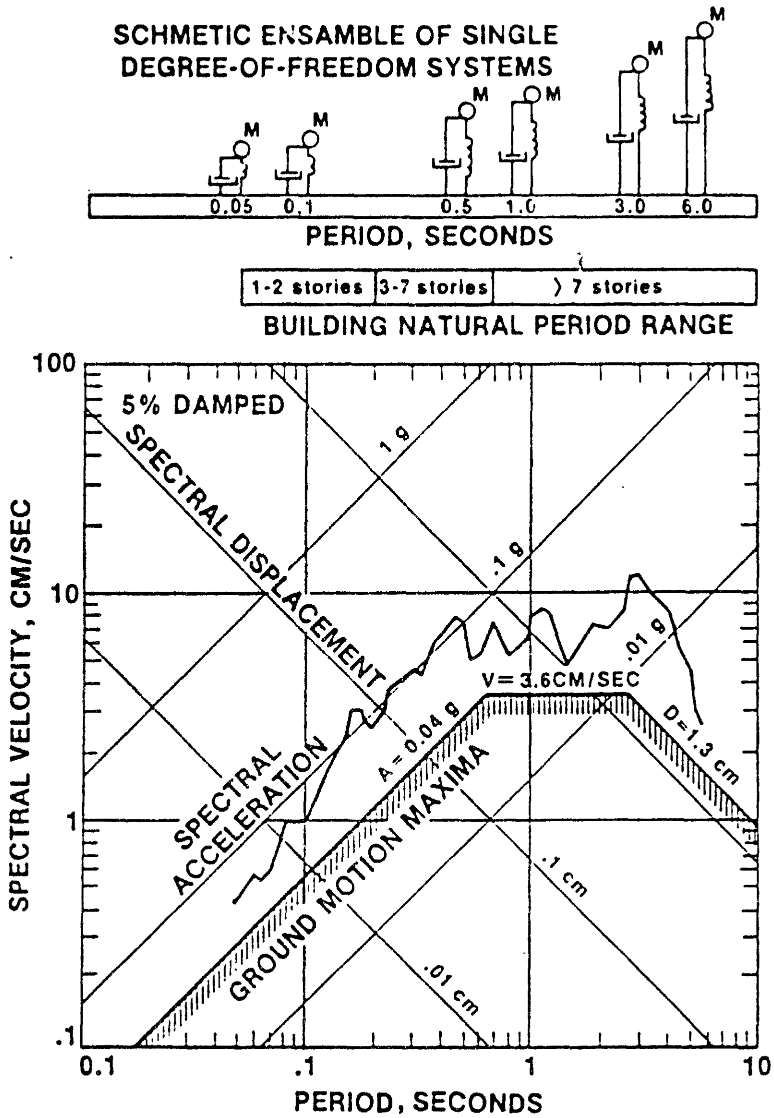
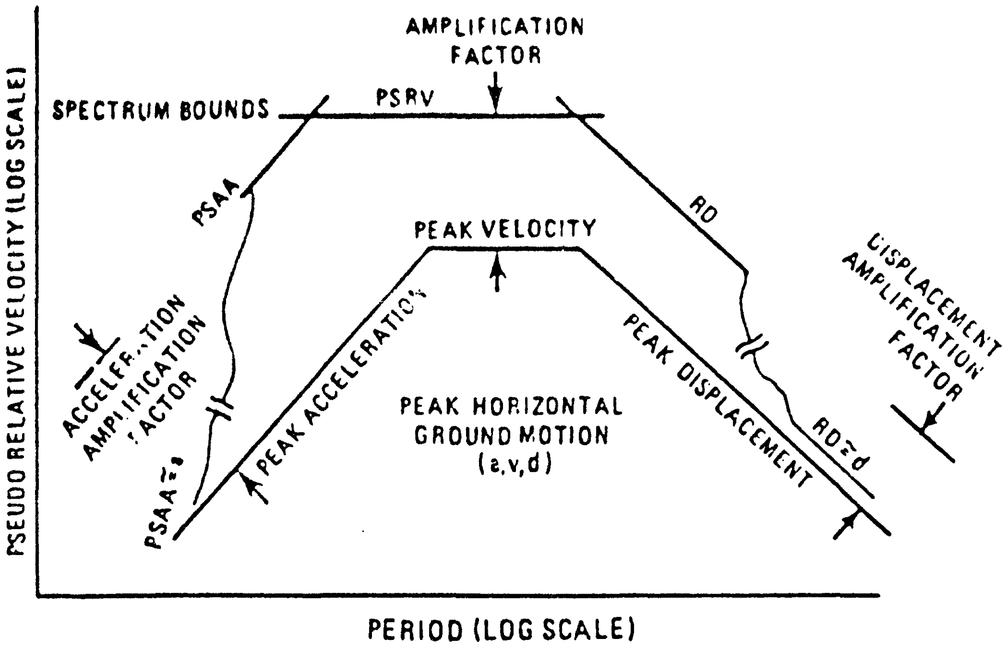
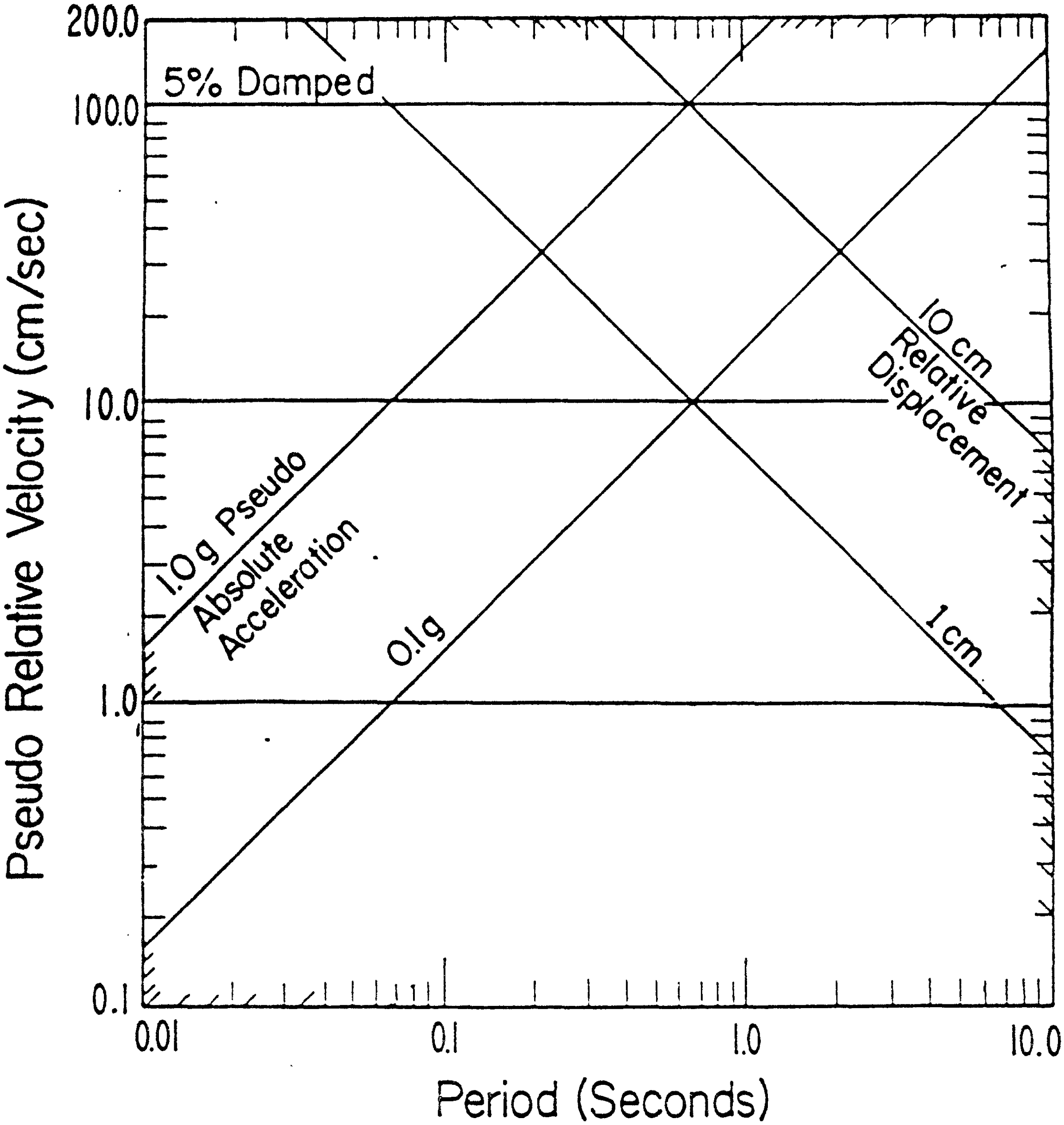


Figure 3.--Graph on tripartite logarithmic paper showing the peak values of ground acceleration, velocity, and displacement and a 5 percent damped response spectrum derived from the acceleration time history.



	AMPLIFICATION FACTOR		
DAMPING (percent)	ACCELERATION	VELOCITY	DISPLACEMENT
0	6.4	4.0	2.5
0.5	5.8	3.6	2.2
1	5.2	3.2	2.0
2	4.3	2.8	2.0
5	2.6	1.9	1.8
7	1.9	1.5	1.4
10	1.5	1.3	1.2
20	1.2	1.1	1.0

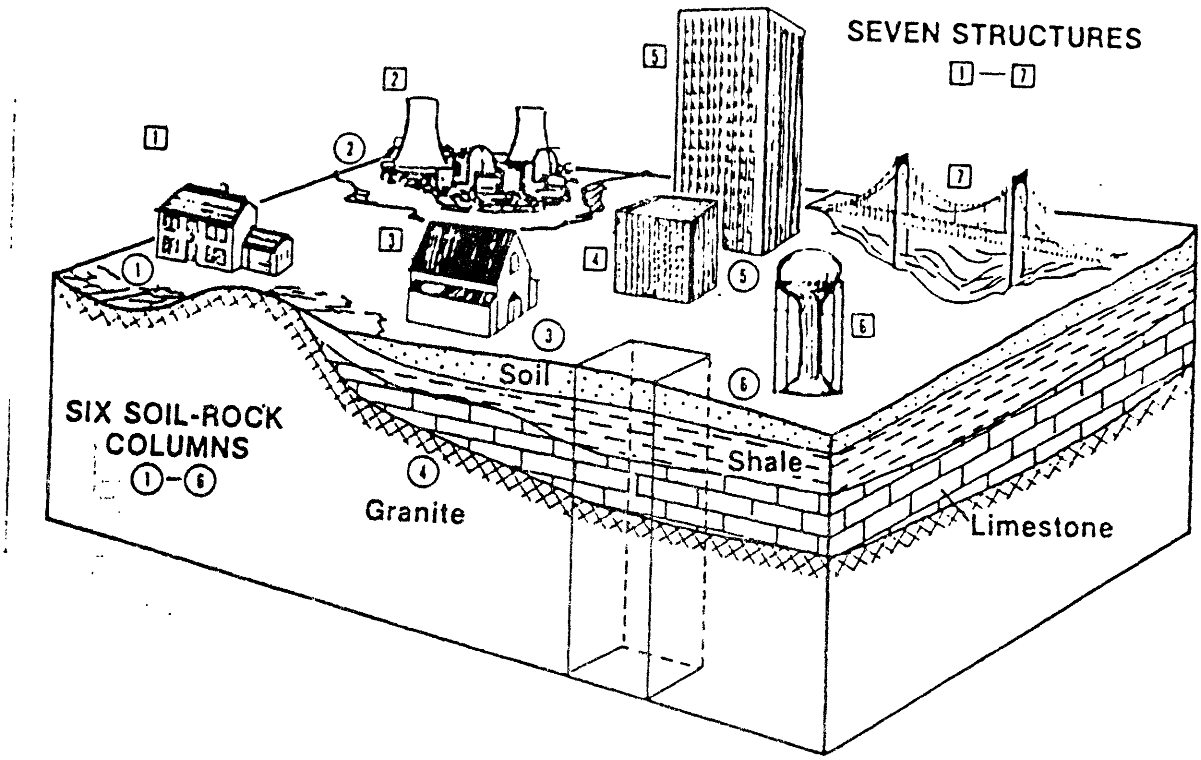
FIGURE 4 —Schematic illustration of technique for developing site-independent response spectra (modified from Newmark and Hall, 1969). The quantities a, v, and d refer to the peak ground acceleration, velocity, and displacement; PSAA, PSRV, and RD refer to the spectral acceleration, velocity, and displacement.



Building Natural Period	1-2 Stories	3-7 Stories	> 7 Stories

Question 2: In earthquake-resistant design, one of the goals is to avoid poor soil-structure combinations (i.e., the condition when $T_s = T_b$) or to accommodate the demand of site response in the design.

SITE AMPLIFICATION OF GROUND MOTION



An equivalent single layer method has been proposed for calculating the characteristic site period, T_s, of a soil deposit. The relation is:

$$T_s = \frac{4H}{RV_s}$$

Where T_s is the characteristic site period in seconds, H is the depth of soil overlying bedrock, V_s is the average shear-wave velocity determined under low strain conditions, and R is a correction factor to allow for the reduction in shear-wave velocity when the soil is excited by high-strain ground motion during an earthquake. Values of R are:

- 0.9 for a bedrock acceleration of 0.1 g.
- 0.8 for a bedrock acceleration of 0.2 g.
- 0.67 for a bedrock acceleration of 0.3 g or greater.

Calculate the characteristic site/periods for three conditions:

A. A 50 m thick soil layer having a shear-wave velocity of 400 m/sec.

B. A 50 m thick soil layer having a shear-wave velocity of 200 m/sec.

C. A 12.5 m thick soil layer having a shear-wave velocity of 200 m/sec.

Assume a location in:

Memphis	A	__________	B	__________	C	__________
Little Rock	A	__________	B	__________	C	__________
Paducah	A	__________	B	__________	C	__________
Popular Bluff	A	__________	B	__________	C	__________
Carbondale	A	__________	B	__________	C	__________
Evansville	A	__________	B	__________	C	__________
Jackson	A	__________	B	__________	C	__________
St. Louis	A	__________	B	__________	C	__________
Your City	A	__________	B	__________	C	__________

D. For cases A, B, and C, determine the worst case--the approximate building height that will make the building period (T_b) equal to the characteristic site period (T_s).

Memphis	A	_____	stories, B	_____	stories, C	_____	stories
Little Rock	A	_____	stories, B	_____	stories, C	_____	stories
Paducah	A	_____	stories, B	_____	stories, C	_____	stories
Popular Bluff	A	_____	stories, B	_____	stories, C	_____	stories
Carbondale	A	_____	stories, B	_____	stories, C	_____	stories
Evansville	A	_____	stories, B	_____	stories, C	_____	stories
Jackson	A	_____	stories, B	_____	stories, C	_____	stories
St. Louis	A	_____	stories, B	_____	stories, C	_____	stories
Your City	A	_____	stories, B	_____	stories, C	_____	stories

E. Experience has shown that the building period lengthens as the damage state increases.

Which case is worse:

- $T_b = 0.5\ T_s$ or
- $T_b = 2.0\ T_s$

Why?

Question 3: The basic cause of liquefaction of sands has been understood qualitatively for many years. If a saturated sand is subjected to ground vibrations, it tends to compact and decrease in volume. If drainage is unable to occur, the tendency to decrease in volume results in an increase in pore water pressure. If the pore water pressure builds up to the point at which it is equal to the over burden pressure, the effective stress becomes zero, the sand loses its strength completely, and it develops a liquefied state.

Liquefaction of a sand may develop in any zone of a deposit where the necessary combination of in-site conditions and vibratory deformations may occur--either at the surface or at some depth below the surface.

The shear stresses developed at any point in a soil deposit during an earthquake appear to be primarily due to the vertical propagation of shear waves in the deposit. Evaluations throughout the world have shown that the average equivalent uniform shear stress is about 65 percent of the maximum shear stress. The approximate number of significant stress cycles depends on the duration of ground shaking and are:

2-3 cycles for M = 5.25
5 cycles for M = 6
10 cycles for M = 6.75
15 cycles for M = 7.5
26 cycles for M = 8.5

Assume ground shaking on the order of 0.1 to 0.2 g. Which site(s) would you avoid if you had a choice of the following four sites for your building:

Site A: A site underlain by fine grained sand with a depth to the water table of 3 m and a shear-wave velocity of 100 m/sec?

Site B: A site underlain by fine grained sand with a depth to the water table of 15 m and a shear-wave velocity of 200 m/sec?

Site C: A site underlain by fine grained sand with a depth to the water table of 30 m and a shear-wave velocity of 400 m/sec?

Site D: A site underlain by fine grained lay with a depth to the water table of 3 m and a shear-wave velocity of 100 m/sec?

Refer to Figures 5, 6, and 7 for guidance in formulating your answer.

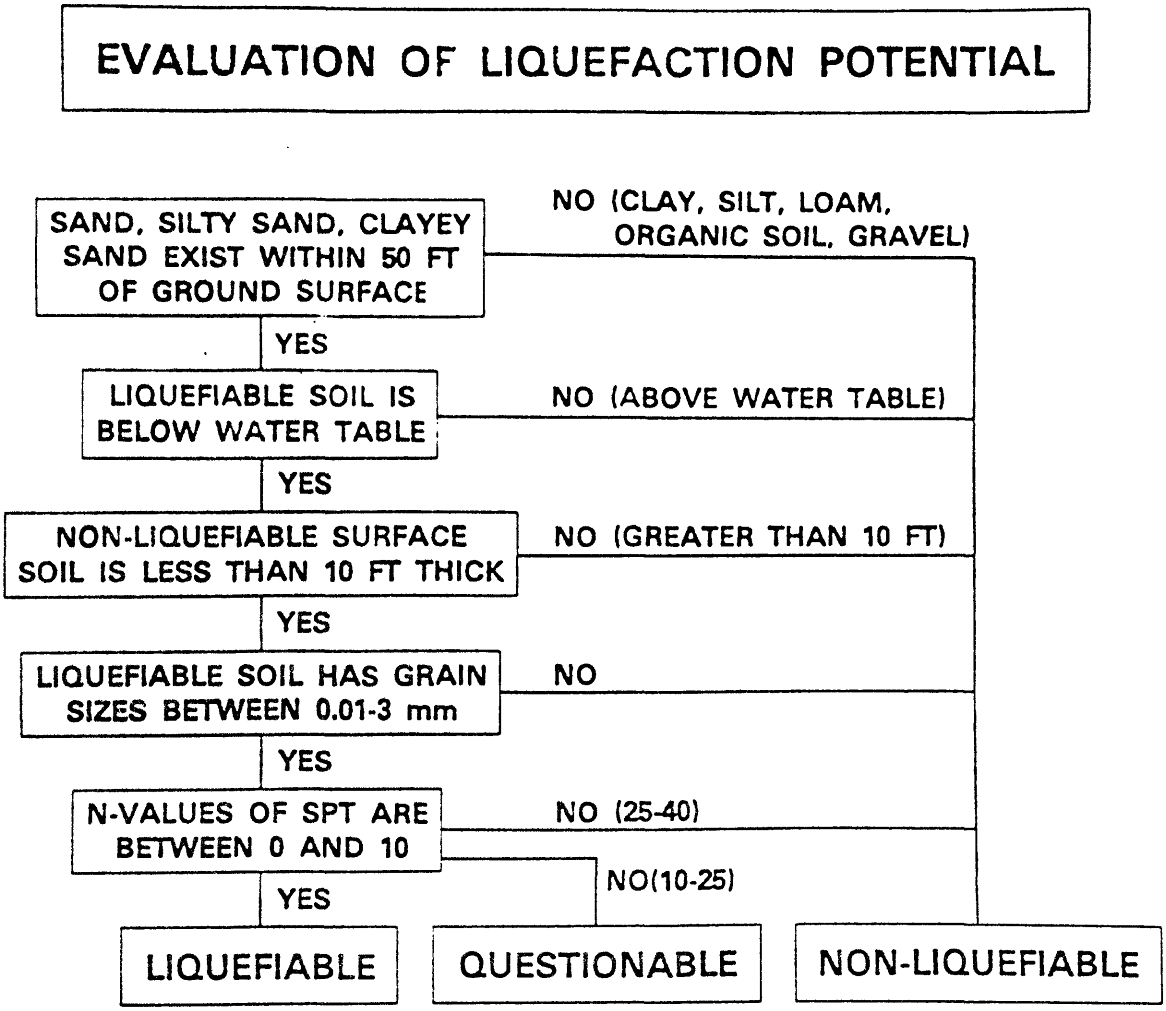


Figure 5.--Diagram showing the factors entering into the evaluation of liquefaction potential at a site exposed to earthquake ground shaking.

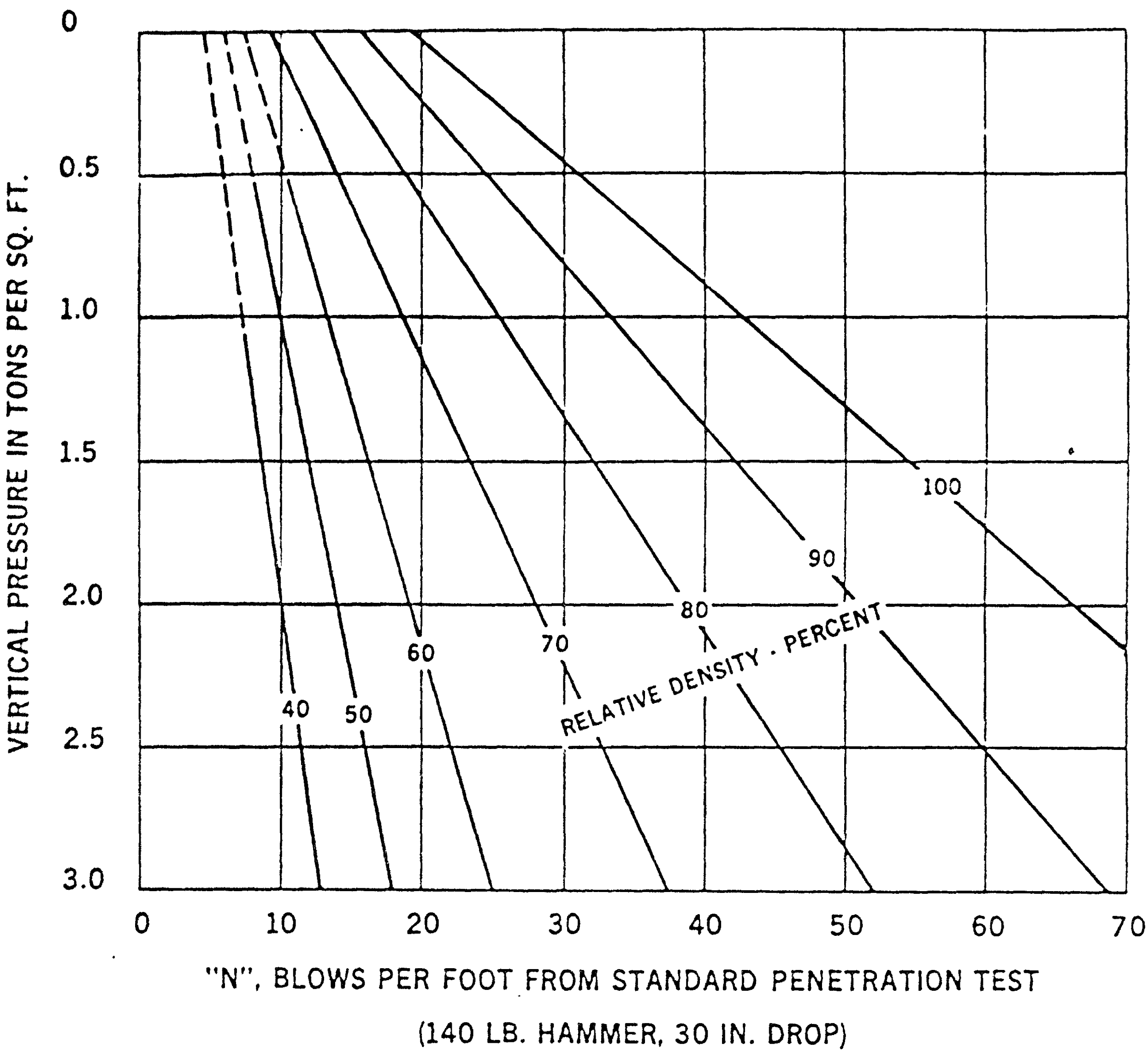


Figure 6.--The Gibbs and Holtz relationship between relative density and SPT blow count (from US-Japan Panel on Wind and Seismic Effects, 1985).

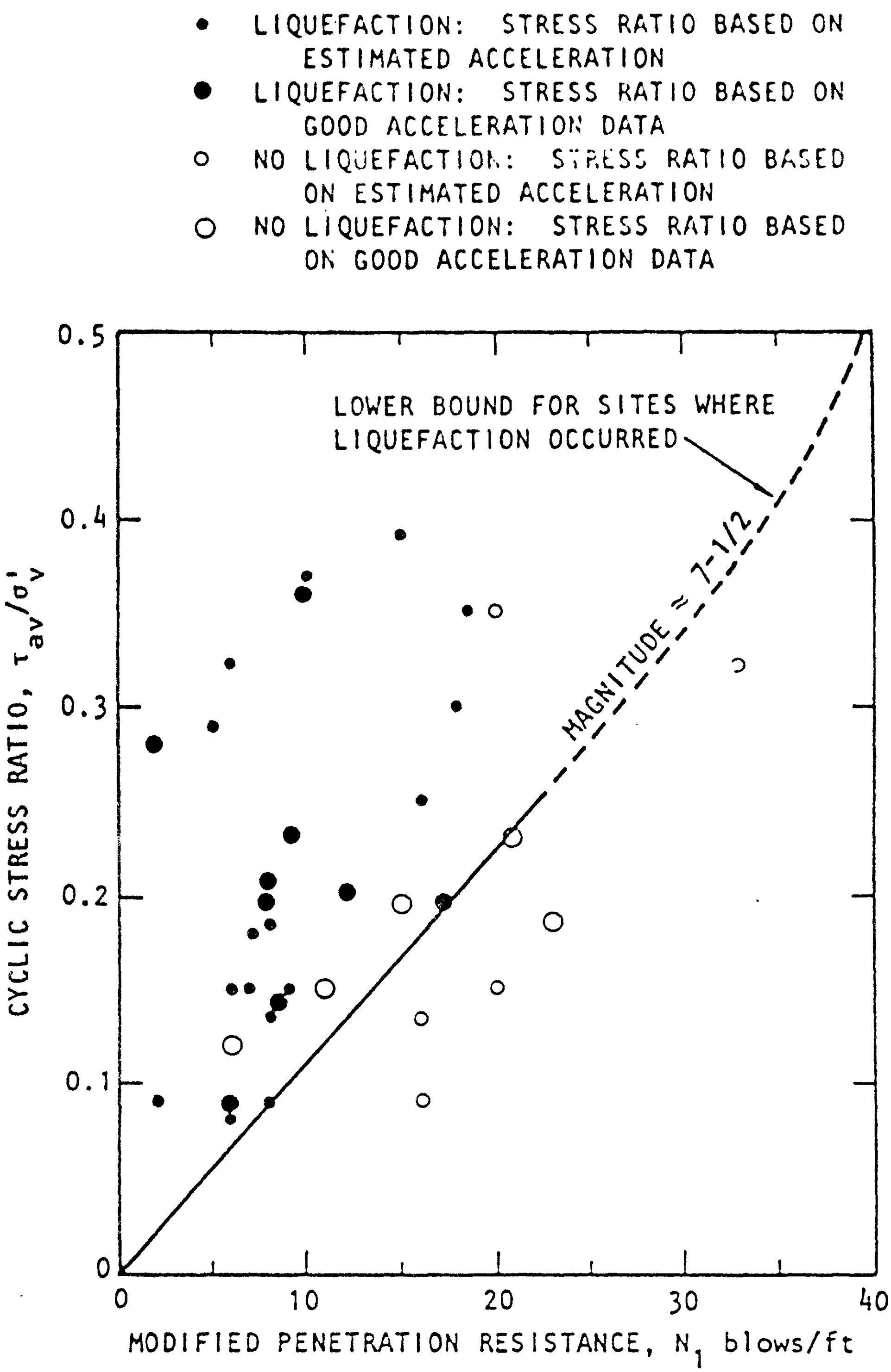
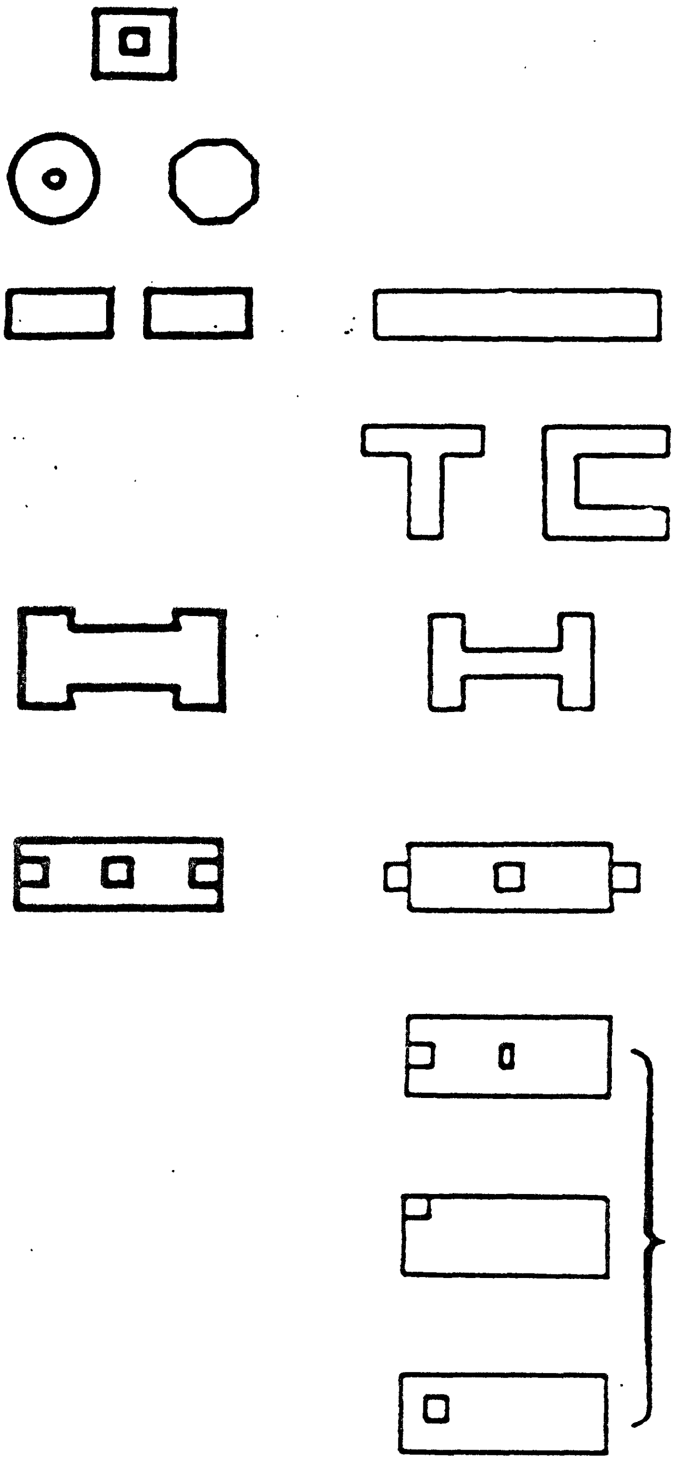
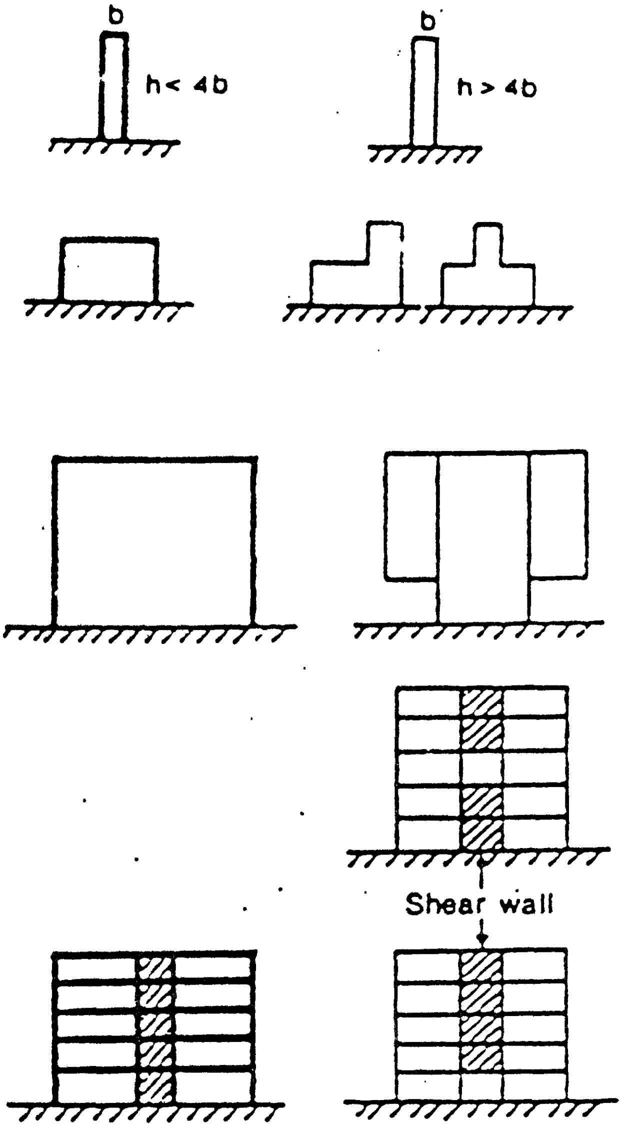


Figure 7.--Correlation between stress ratio causing liquefaction in the field and penetration resistance of sand (from Seed and Idriss, 1982).

Question 4: Refer to the building plan layouts below. For each one, state the positives (if any) and negatives of each layout from the perspective of a seismic design.




b
h< 4b
b
h > 4b
Shear wall

Question 5: Answer the following questions concerning the design and construction of earthquake-resistant buildings.

A. Determine the 1988 UBC design base shear force (V) for a 10-story ductile moment-resisting steel-frame office building located in Shelby County, Tennessee, on soil type 2. The story heights are all 13 ft.; the plan area is 60 ft. by 100 ft. The total dead load is 100 psf at all levels.

B. Determine the 1988 UBC design base shear force (V) for a 6-story reinforced masonry bearing wall hospital building located in Shelby County, Tennessee, on soil type 1. The story heights are all 10 ft.; the plan area is 60 ft. by 100 ft. The total dead load is 120 psf at all levels.

C. For the same building described in Problem A, determine the 1988 NEHRP design base shear force (V).

D. For the same building described in Problem B, determine the 1988 NEHRP design base shear force (V).

E. For the same building described in Problem A, determine the design base shear force (V) for wind loading.

$$V = p \times (\text{Projected Building Area}) \times I$$

where p = design wind pressure (psf);
I = importance factor (same as used in seismic loading).

Assume p = 12.7 psf for 0 ft. to 20 ft. above ground;
14.6 psf for 20 ft. to 40 ft. above ground;
18.2 psf for 40 ft. to 60 ft. above ground;
20.0 psf for 60 ft. to 100 ft. above ground;
23.7 psf for 100 ft. to 150 ft. above ground.

F. For the same building described in Problem B, determine the design base shear force (V) for wind loading. Assume same wind loading distribution as described in Problem E.

Table A - Powers of Numbers

T	$T^{2/3}$	h or L	$L^{1/2}$	$L^{3/4}$
0.10	0.22	10	3.16	5.62
.20	.34	20	4.47	9.45
.30	.45	30	5.48	12.82
.40	.54	40	6.32	15.91
.50	.63	50	7.07	18.80
.60	.71	60	7.74	21.56
.70	.79	70	8.37	24.20
.80	.86	80	8.94	26.75
.90	.93	90	9.48	29.22
1.00	1.00	100	10.00	31.62
1.10	1.06	110	10.49	33.96
1.20	1.13	120	10.95	36.26
1.30	1.19	130	11.40	38.50
1.40	1.25	140	11.83	40.70
1.50	1.31	150	12.25	42.86

HOMEWORK

1. Suppose you are requested by your city administration to recommend an implementing strategy for reducing potential losses from future earthquakes in your community. What would you recommend to make existing physical development safer, focusing on:

   A. Faults.
   B. Ground motion hazard.
   C. Ground failure hazard.
   D. Flood hazard.
   E. Hazardous materials.
   F. High occupancy buildings.
   G. Hazardous buildings.
   H. Critical facilities.
   I. Nonstructural hazards.
   J. Rebuilding.

COURSE 4

LOSS REDUCTION

A READER ON EARTHQUAKE HAZARD REDUCTION IN THE CENTRAL UNITED STATES

CONTENTS

THE DECADE FOR NATURAL DISASTER REDUCTION

Each year natural disasters kill tens of thousands of people and inflict billions of dollars in economic losses. No nation nor community is immune from their damaging impact. Recent examples of the human suffering and economic costs exacted by natural disasters include the December 7, 1989 Armenian earthquake, in which an estimated 25,000 died; the 1988 flooding in Bangladesh, which inundated approximately 80% of that country and disrupted its social and economic fabric; and a relatively minor 1987 earthquake on the Whittier Narrows fault in California that caused direct property losses in excess of $350 million. Further, statistics show that our losses are mounting as populations increase and concentrate in vulnerable urban and coastal areas. Clearly, the need to reduce the toll of natural disasters is urgent.

The scientific and technological advances of the last half century provide unprecedented opportunities for mitigating the impacts of natural hazards. Recognizing this, Dr. Frank Press, President of the U.S. National Academy of Sciences, proposed an international decade to address this problem/opportunity at the Eighth World Conference on Earthquake Engineering in 1984. In 1987, the United Nations General Assembly adopted a resolution declaring the 1990s as the International Decade for Natural Disaster Reduction, "a decade in which the international community will pay special attention to fostering cooperation in the field of natural disaster reduction", and the U.S. Senate and House of Representatives endorsed the Decade concept in resolutions passed the following year.

The Decade will focus primarily on natural disasters caused by windstorms (hurricanes, cyclones, thunderstorms, and tornadoes), floods, earthquakes, volcanic eruptions, landslides, tsunamis, wildfires, and the rapid-onset aspects of drought and locust infestation. Strategies for reducing losses will stress prevention and preparedness while sustaining and enhancing critical disaster response, relief, and recovery capabilities. Other issues that may be considered as the Decade progresses are the relationship between the prevalence of natural disasters and global environmental change, as well as technological disasters that occur as the result of a natural event.

Among the greatest challenges of the Decade will be the development of broad public support and political will to implement loss reduction programs. The involvement and commitment of our society's full resources, including individuals and community organizations; voluntary and professional organizations; the private sector; academic institutions; and federal, state, and local governments, will be necessary. Cooperative efforts in support of a focused Decade program will enhance our ability to protect lives and property from disaster and lead to a safer, more productive world for all.

FROM IDEA TO REALITY: THE DECADE FOR NATURAL DISASTER REDUCTION

Ideas are the stuff of which the human world is made. Mankind is at its best when turning some simple, fundamental idea into reality. Many of the great achievements of history can be seen as the "realization" of a very basic idea.

Columbus, who knew that he would not fall off the edge of the world if he sailed out of charted waters, had the idea that if he headed far enough west he would surely strike land--hopefully a land that would prove to be profitable. The acting on this idea, he created a new reality for himself and the world.

The Decade for Natural Disaster Reduction, recently proclaimed by the United Nations for the 1990s, also began as an idea or set of ideas: the world need not continue to suffer devastating losses as a result of natural disasters. These losses are unnecessary because new technology gives us the wherewithal to prevent much of the loss of life and property that result from natural hazards. The very existence of such a potential constitutes a moral imperative to action.

Action, of course, is what translates an idea into reality.

If the idea of a world safer from the ravages of natural disasters is to become a reality, a program of action must be undertaken to reduce their impact. The activities of the Decade will constitute such a program of action.

The Decade for Natural Disaster Reduction is the first coordinated effort to prevent the unnecessary loss of life and property from natural disasters. It is an opportunity for individual communities and the world community as a whole to use the considerable existing scientific and technical knowledge to alleviate human suffering and enhance economic security.

Each year natural disasters kill tens of thousands of people and inflict billions of dollars in economic losses. No nation nor community is immune from their damaging impact. In just the two that struck the United States in 1989, the Lama Prieta earthquake and Hurricane Hugo, over 116 lost their lives and economic losses exceeded $14.6.

The Decade will focus primarily on natural disasters caused by earthquakes, windstorms (hurricanes, tornadoes, thunderstorms, cyclones), floods, volcanic eruptions, landslides, tsunamis, wildfires, and drought. A basic premise is that although critical response capabilities must be supported and improved, our greatest gains will be made through exerting greater efforts in the areas of preparedness and mitigation.

The concept of a cooperative international program to reduce natural disasters was first presented by Dr. Frank Press, president of the U.S. National Academy of Sciences, in a speech at the Eighth World Conference on Earthquake Engineering in 1984. In his keynote address to the International Association for Earthquake Engineering (IAEE), he proposed an International Decade for Natural Hazard Reduction, beginning in 1990. He noted that we could not control the forces of nature but we could do much to limit their calamitous impacts.

After the 1984 conference, as copies of Dr. Press' speech circulated, international interest began to build, and over the past five years the Decade concept has gathered international support from scientists, engineers, sociologists, educators, emergency relief organizations, private industry, governments, and the United nations.

Also during this time, the U.S. National Academy of Sciences formed an Advisory Committee on the International Decade. This committee, consisting of many of the U.S.'s leading disaster-mitigation experts, and with input from Canada, Mexico, and Japan, produced the report, Confronting Natural Disasters, (photocopies available upon request) which evaluated the potential for a Decade effort and the best means to implement it on an international scale. A subsequent report, Reducing

Disasters' Toll, (available on request) examined the need and opportunity for a Decade within the United States.

These and other events fueled further interest in the Decade and eventually came to the attention of Secretary-General Perez Cuellar of the United Nations. Subsequently the Governments of Morocco and Japan--whose recognition of the Decade's import and whose dedication to its realization were invaluable--cosponsored a resolution designating the 1990's as "...a decade in which the international community, under the auspices of the United Nations, will pay special attention to fostering international cooperation in the field of natural disaster reduction..."

In response to this resolution, the Secretary-General called for the establishment of national committees. At the request of agencies of the federal government, a U.S. National Committee for the Decade for Natural Disaster Reduction was formed in the National Research Council (NRC), the operative arm of the National Academy of Sciences.

The Committee has a diverse and prestigious membership chosen to include all the disciplines and sectors that are necessary to a successful disaster reduction program. It is chaired by Dr. Richard Hallgren, former Director of the National Weather Service. Among its members are individuals drawn from the media, private industry, and academia, as well as city, state, and federal governments. One especially v the Committee is Lacy Suiter, Director of the Te Management, who is ably supported in this activity by and Harvey Ryland.

This Committee has met on four occasions since June 1989 and is working to define a Decade program for the U.S. It has identified several areas in which the nation should concentrate its efforts to reduce the toll of natural disasters:

- Awareness and education entails making all sectors of American society--individuals, private industry, the media, professional associations, academia, nongovernmental organizations, public officials, and local, state, and federal governments--aware of the natural hazards that face them and the actions they can take to protect themselves. An example of the kind of activity that would characterize this program focus would be the launching of an information campaign aimed at the public. Through all forms of the media--print, television, and radio--basic information on disaster preparedness and response procedures would be made available to the public and every household would be encouraged to develop a survival plan.

- Mitigation is characterized by efforts aimed at preventing loss of life, property damage, and economic losses associated with the potential occurrence of natural hazards. Mitigation activities should include such simple nonstructural measures as securing bookcases and water heaters to walls so that they do not fall during an earthquake, as well as construction of new buildings and retrofit of existing structures to ensure the survival of their occupants during a hazardous event. The Committee is likely to recommend that governments, at all levels, take the lead by requiring that all new buildings constructed for their use be disaster resistant.

o <u>Preparedness for emergency response</u> is the detailed planning for prompt and efficient response once a natural disaster occurs. Every community should have a detailed plan for actions to be taken in the wake of a disaster. Among the items that should be included are an inventory of the equipment and human resources that would be used in the aftermath. This should include their location and procedures for deployment. Similar information should be gathered on critical relief supplies such as food, water, medicine, and shelter. Mutual aide agreements with neighboring communities should be drawn up in advance to ensure that these needs will be met quickly and efficiently event if the scope of a disaster exceeds the capacity of the community to supply itself. Preparedness plans should also identify roles for all likely participants and regular exercises should be held to ensure their effectiveness. In this regard it is important to recall that the victims are always "the first people on the scene" and are, thus, a vital part of the response effort.

- <u>Preparedness for recovery and reconstruction</u> is detailed planning for rapid restoration of normal community functioning and the implementation of safeguards against future events after a natural disaster. As tragic as they may be, disaster also present an opportunity--the opportunity to improve the hazard resistance of a community by rebuilding it in a safer manner. Again, Hurricane Hugo and the Lama Prieta earthquake provide excellent examples of the value of this type of preparedness. In northern California, where recovery and reconstruction plans were well developed, normal community life was restored within days. In South Carolina, where evacuation plans were excellent but postdisaster planning was not stricken communities are still struggling to recover.

- <u>Prediction of hazardous events and dissemination of warnings</u> includes providing forecasts, alerts, and predictions for impending or potential events and their dissemination through technical and societal systems. Although scientists are not yet able to accurately predict the occurrence of an earthquake, they are working on it and that work should be supported. Even a warning received only two minutes before an event gives potential victims some time to protect themselves.

- o <u>Postdisaster strategies</u> entail the collection and sharing of information after a disaster and the use of the "window of opportunity" to promote further disaster reduction programs after such events. For example, valuable information on the behavior of buildings and soils can be obtained after earthquakes such as those that have occurred in San Francisco in this century. This type of information is of value, not only to San Francisco, but also to communities that face a similar threat throughout the nation and the world.

Of course, the country has made significant progress in reducing its vulnerability to natural disasters over the last twenty to thirty years. In the central United States, CUSEC (the Central United States Earthquake Consortium) has been working for 8 years to ready Arkansas, Illinois, Indiana, Tennessee, Kentucky, Missouri, and Mississippi for the inevitable earthquake. Fortunately, these efforts have not yet been put to the test, but as successes in the recent earthquake and hurricane demonstrated, there is much that can and has been done to save lives and limit property losses. At the same time, however, failures such as the collapse of the Cypress Freeway in Oakland point out the need to do more. The Decade for Natural Disaster Reduction provides the impetus to meet that need.

The idea of the Decade is well on its way to becoming a reality. It has not yet, however, arrived. Just as Columbus needed the participation of Queen Isabella and a worthy crew, so the Decade needs strong backers and many good hands on deck.

It is gratifying to note that there are already some recruits. The Decade has been endorsed by the U.S. Senate and House of Representatives; the states of Tennessee, California, and Utah; and the cities of Memphis and Boulder, Colorado. Several professional associations around the country--the American Society of Civil Engineers, the American Association of Engineering Societies, the American Institute of Architecture, and others--are developing workshops and other programs to focus and advance their contributions to the Decade.

This represents a fine beginning, but it is not enough. If the Decade is to succeed in making the world safer from natural disasters, we must be drawing on the commitment and active participation of at least 10,000 individuals--on your commitment and active participation.

Your participation is critical, as an individual and as a professional. The Decade is a challenge to you to examine the ways that you can contribute to creating a more disaster resistant world in your home, your job, and your community.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

APPLICATIONS OF KNOWLEDGE PRODUCED IN THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM: 1977 - 1987

AN INTERPRETATIVE REPORT BASED ON THE REPORT
"A REVIEW OF EARTHQUAKE RESEARCH APPLICATIONS IN THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAM: 1977-1987"
SHOWING WHAT HAS BEEN LEARNED ABOUT APPLICATIONS TO MITIGATE THE EARTHQUAKE HAZARD

Sponsored by:

The Federal Emergency Management Agency,
The National Institute of Standards and Technology,
The National Science Foundation, and
The U.S. Geological Survey

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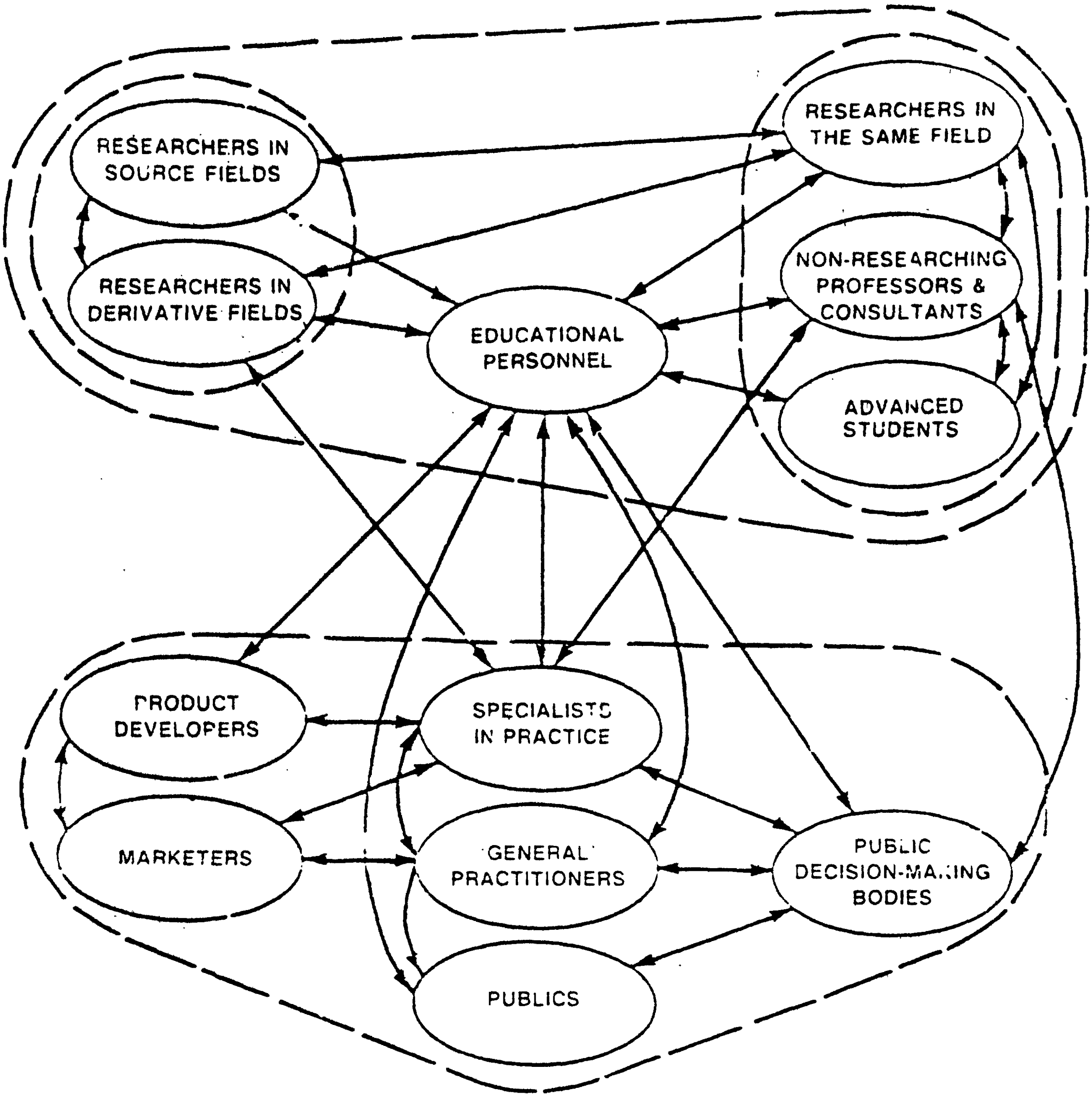
Reston, Virginia
1988

RESEARCH INFORMATION NETWORK



PRACTICE IMPROVEMENT INFORMATION NETWORK

EXECUTIVE SUMMARY

APPLICATIONS OF KNOWLEDGE PRODUCED IN THE NATIONAL EARTHQUAKE HAZARDS REDUCTION PROGRAMS 1977-1987

INTRODUCTION

This report defines what has been learned about mitigating the earthquake hazard throughout the nation--the goal of the National Earthquake Hazards Reduction Program (NEHRP)--after 10 years of work and an expenditure of 610 million dollars by the four principal agencies of the NEHRP. It contains recommendations that build on the major accomplishments of the first decade of the NEHRP and extend and strengthen the capability for achieving earthquake hazard mitigation in every part of the nation during the second decade. It also calls for the four principal agencies, the Federal Emergency Management Agency (FEMA), the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), and the United States Geological Survey (USGS) to work together to set priorities within the framework of their missions and to consider and adopt changes in their current programs that will accelerate progress in:

- research,
- development of professional practices, and
- implementation of loss-reduction measures that will mitigate or reduce the earthquake hazard in every part of the nation during the second decade of the NEHRP.

The report points out the urgent national need to realize objectives such as:

- Understanding the seismic cycle of the nation's seismogenic zones.
- Dealing with the enormous number of existing buildings throughout the nation that have a high potential for collapse in an earthquake.
- Eliminating and/or strengthening the large number of unsafe school buildings in the United States.
- Improving the siting, design, and construction of the nation's new buildings and facilities, valued annually at about 397 billion dollars.
- Enhancing the skills of the nation's professionals to apply the large body of available knowledge to mitigate the earthquake hazard.

- Increasing the state-of-preparedness in urban centers throughout the nation.
- Producing many more "champions" of earthquake hazard mitigation.

This report is a companion to and an interpretation of another report entitled, "A Review of Earthquake Research Applications in the National Earthquake Hazards Reduction Program: 1977-1987." Both reports were published as U.S. Geological Survey Open-File Report 88-13. Together, they provide sixty case histories of research applications in various parts of the United States and a synthesis of the conclusions and recommendations. The two reports represent the contributions and thoughtful review of over one hundred men and women ("champions") who have provided leadership in all regions of the United States for applications of knowledge to mitigate the earthquake hazard.

UNIOUENESS OF THE EARTHQUAKE HAZARD

Unlike other natural hazards such as floods, hurricanes, landslides, and volcanic eruptions, earthquakes are unique in their potential for causing great sudden loss. They have struck and will again strike urban centers throughout the United States with little or no warning, causing great physical and societal impacts over a broad geographic region within a few seconds to a few minutes. Without adequate preparedness and mitigation measures in place, an urban center faces the threat of damage and destruction of buildings, lifeline systems, and critical facilities as well as death, injury, homelessness, and joblessness for the populace. Economic losses can potentially reach a few to several tens of billions of dollars in many urban centers of the nation. The primary phenomena to be mitigated are ground shaking and permanent ground failure. The secondary phenomena to be mitigated are surface fault rupture, regional tectonic deformation, tsunamis, seiches, fire following earthquakes, flooding from dam failure, and the effects of aftershocks. A large percentage of the nation's 215 million people live in urban centers of the nation having a moderate to high risk of experiencing at least one damaging earthquake in their lifetime. Whether or not the event will produce a disaster depends on the earthquake preparedness and mitigation measures in place at the time of the earthquake.

CASE HISTORIES

Using a knowledge utilization model proposed in 1985 by Yin and Moore, sixty case histories were compiled, categorized, and evaluated in terms of enlightenment uses, decisionmaking uses, and practice uses. Collectively, the case histories dealt with: 1) primary and secondary earthquake phenomena, 2) physical, social, and economic models of urban and regional systems, 3) varying degrees of public and private apathy regarding the earthquake threat, which often is perceived as an infrequent, low-salience problem, and 4) strategies available for controlling and mitigating potential losses.

The case histories showed that applications of knowledge to protect people and property throughout the nation have happened as a consequence of a complex dynamic process (called herein the research applications process) linking knowledge producers (researchers) and knowledge users (practitioners). In this process, researchers typically produce fundamental knowledge answering the questions:

- What has happened in the past?
- What can happen in the future?
- Where did it happen?
- When will it happen?
- Why did it happen?
- How bad were the physical effects?
- How often will they recur?
- How did the populace behave?
- What can be done to keep these physical phenomena from causing damage, deaths, injuries, and loss of function?

From this knowledge base, products have been prepared and disseminated, including: hazard maps, land use plans, engineering standards, model building codes, methods for testing, methods for estimating loss of life and economic loss, and methods for improving regional, community, and personal preparedness. Practitioners take these products and determine if they can be used in their community to mitigate the hazard in a way that:

- will save lives,
- will reduce damage and economic loss,
- will reduce social and economic disruption,
- is in line with community values, is feasible, and is affordable.

COLLABORATION OF CHAMPIONS

The two most significant factors in the research applications process are activities that: 1) produce champions of earthquake hazard mitigation, and 2) give them a reason for collaboration. The research applications process works best when researchers and practitioners collaborate as partners on the same program. However, this goal is difficult to achieve because: 1) the researchers (typified by physical and social scientists and engineers) and the practitioners (typified by state and local government officials, investors, developers, insurers, professional and voluntary organization, engineers, and specialized consultants) do not collaborate naturally, and 2) there is a big difference in their perspectives. Effective collaboration happens over a period of time ranging from years to a decade or more as trust is built.

CRITICAL FACTORS

The critical factors for an effective earthquake-hazard-mitigation partnership are:

- A need and demand for research, development of practices, and applications - The need and demand must come from all levels of the partnership whose individual members are alert to windows of opportunity.

- People who are competent and motivated to lead and work cooperatively in research, development of practices, and applications - These individuals provide leadership, function as internal advisors and advocates, serve as external champions, and collaborate daily to advance the state-of-knowledge and state-of-practice.

- Resources that are adequate for research, development of practices, and applications - These resources facilitate the creation of timely programs and the balancing of technical, societal, and political considerations.

- Products that are capable of being used in practical applications to reduce and mitigate the earthquake hazard - These products must be based on a sound knowledge base and be credible and practical.

RECOMMENDATIONS

Looking ahead to the urgent needs of the nation and the challenges of the second decade of the NEHRP, the participants raised the issues of leadership, funding, priorities, and changes in programs to accelerate progress. While acknowledging on the one hand that major and significant advances were made in every part of the nation during the first decade and recognizing on the other hand that every part of the nation still needs to do many things to reduce or mitigate their earthquake hazard, the following recommendations were offered to the four principal agencies of the NEHRP for consideration. They are given in terms of the four themes of the fourth workshop:

1) Policies, programs, and practices - The four principal agencies of the NEHRP should collaborate more closely to eliminate and correct all perceived differences in agency policies, programs, and practices that have kept and will unless corrected continue to keep the goals of earthquake hazard mitigation in every part of the nation from being realized. Issues like leadership, coordination of Agency missions and programs, funding, and the forging of partnerships at all levels throughout the nation should be dealt with forthrightly and expeditiously.

2) Enhancing collaboration between researchers and practitioners - The four principal agencies of the NEHRP should be a model of collaboration for the nation because they represent the nation's researchers (NSF, USGS, and NIST) and practitioners (NIST and FEMA).

As a model for the nation to follow, the agencies shoul' seed new and more effective ways to produce champions of earthquake hazard mitigation in the ranks of researchers and practitioners at all levels in the nation and to improve their collaboration.

3) Strengthening the research applications process - The complex long term process involving an interrelated network of people, events, ideas and methods of communication between researchers and practitioners must be made as strong as possible.

The four principal agencies should seek creative ways to improve the way the research applications process works. The process consisting of research, dissemination, communication, applications, and evaluation should be defined in a way that involves more champions of earthquake hazard mitigation during the second decade of the NEHRP.

The agencies should collaborate to strengthen their missions and funding. For example:

- NIST - should seek additional funding and lead out more in the application of engineering and scientific research by undertaking tasks ranging from testing the practicality of research results produced and/or sponsored by the USGS and NSF to writing and disseminating engineering standards and model codes for buildings and lifeline systems.

- FEMA - should seek additonal funding and lead out more in two areas: emergency preparedness and implementation. FEMA should utilize the technology developed and disseminated by NIST within the political and bureaucratic process to foster implementation of loss-reduction measures by state and local governments and the private sector.

- NSF - should seek addiatonal funding and lead out more in engineering, scientific, and social science research while providing support for applications.

- USGS - should seek additional funding and lead out more in scientific research while providing support for applications through special assignments of personnel as well as through grants.

4) Priorities

The four principal agencies should strengthen their resources and resolve for carrying out their individual missions, setting national priorities that will meet the urgent needs of the nation. For earthquake hazard mitigation, programs should balance the dual need for research and applications, focusing on highest priority national needs such as the following partial unranked list:

- Producing many more champions of earthquake hazard mitigation at all levels of government and in academia and the private sector.
- Creating programs that bring "champion researchers" and "champion practitioners" together.
- Making existing hazardous buildings safer.
- Siting and designing new construction and lifeline systems to withstand the ground shaking and ground failure hazards.
- Enhancing professional skills.
- Quantifying the seismic cycle of seismogenic zones.
- Increasing the state-of-preparedness in urban centers.

THE FUTURE

Implementation of these recommendations will make our nation safer from the earthquake threat. One outcome will be that a moderate magnitude earthquake like the December 7, 1988, Soviet Armenia earthquake will not be a disaster when some part of our nation is struck in the future. The magnitude 6.8 Armenia earthquake, which left an estimated 60,000 dead, 18,000 injured, 510,000 homeless, and reconstruction costs in Armenia reaching $16 billion, raised the sobering question: **Can a similar disaster happen in the United States?**

The answer to this hypothetical question depends on the accomplishments of the first decade of the NEHRP and what will be done in the second decade. **The answer is probably "yes" if such an earthquake happened tomorrow in almost all parts of the nation, except California, because three key mitigation strategies have not been fully implemented throughout the nation:**

- **Design and construction of new buildings to be earthquake resistant.**
- **Removal or strengthening of existing hazardous buildings.**
- **Preparedness planning and implementation of mitigation measures in earthquake-prone urban centers.**

The answer would probably be "no" if the earthquake happened a decade from now, provided that these three actions have been realized throughout the nation.

The United States has been challenged to join with, and indeed to lead, other nations throughout the world in concerted actions to make the 1990's a "decade of disaster reduction." This period, called the International Decade for Natural Disaster Reduction (IDNDR), is dedicated to improving and invigorating efforts to reduce the economic and death tolls from natural hazards such as earthquakes, floods, hurricanes and tornadoes, landslides, volcanic eruptions, tsunamis, wildfires, drought, and locusts. The need for reducing the economic toll from earthquakes and other natural hazards in the United States is urgent. The United States has a large number of seismogenic zones, active volcanoes, thousands of miles of storm-prone coastline, large and small flood-producing river systems, slopes susceptible to landslides, coasts susceptible to tsunami runup, and wilderness/urban interacts vulnerable to wildfires. Every year, economic losses from all natural hazards average about 10 billion dollars.

The economic losses will continue to increase as the nation builds and expands its communities along the water's edge, on floodplains, in earthquake-prone regions, on unstable slopes, in zones susceptible to volcanic eruptions, and at wilderness interfaces susceptible to wildfires unless mitigation measures are put in place simultaneously with the development.

THE RESEARCH APPLICATIONS PROCESS

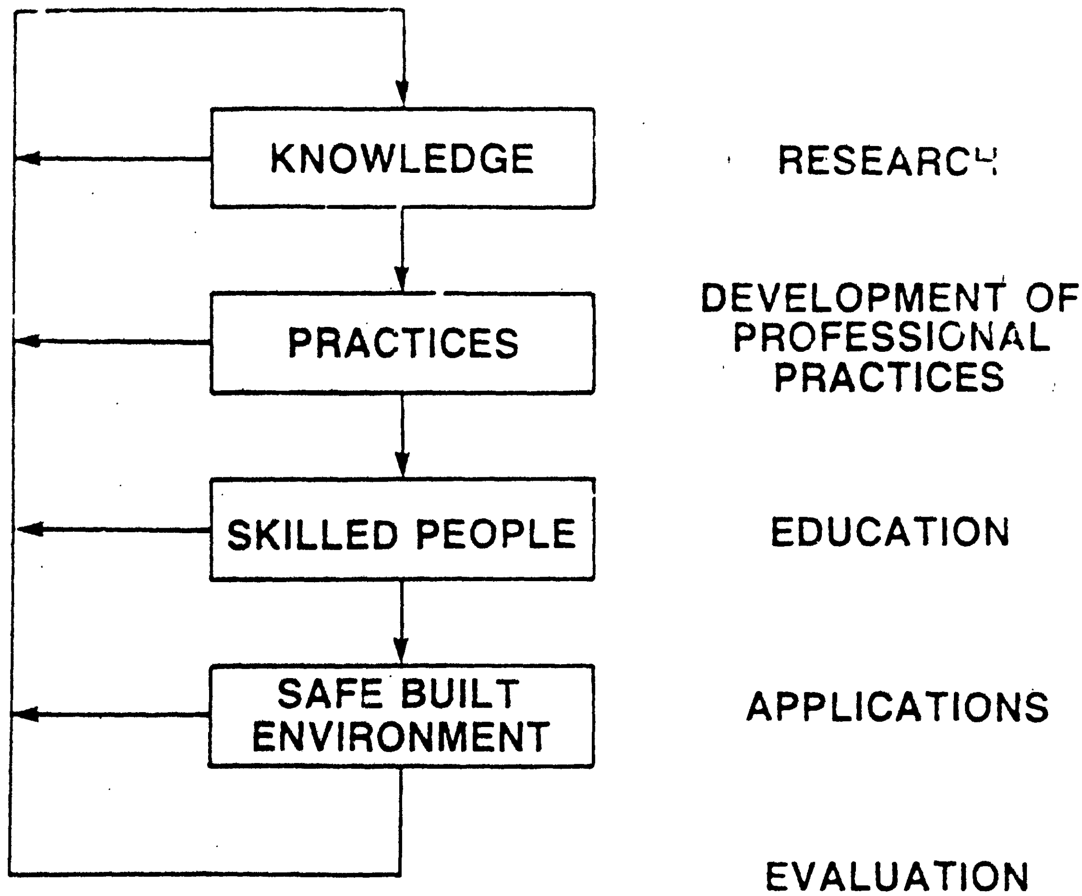


Figure 1:--Schematic illustration of research applications process (from Richard Wright, NIST).

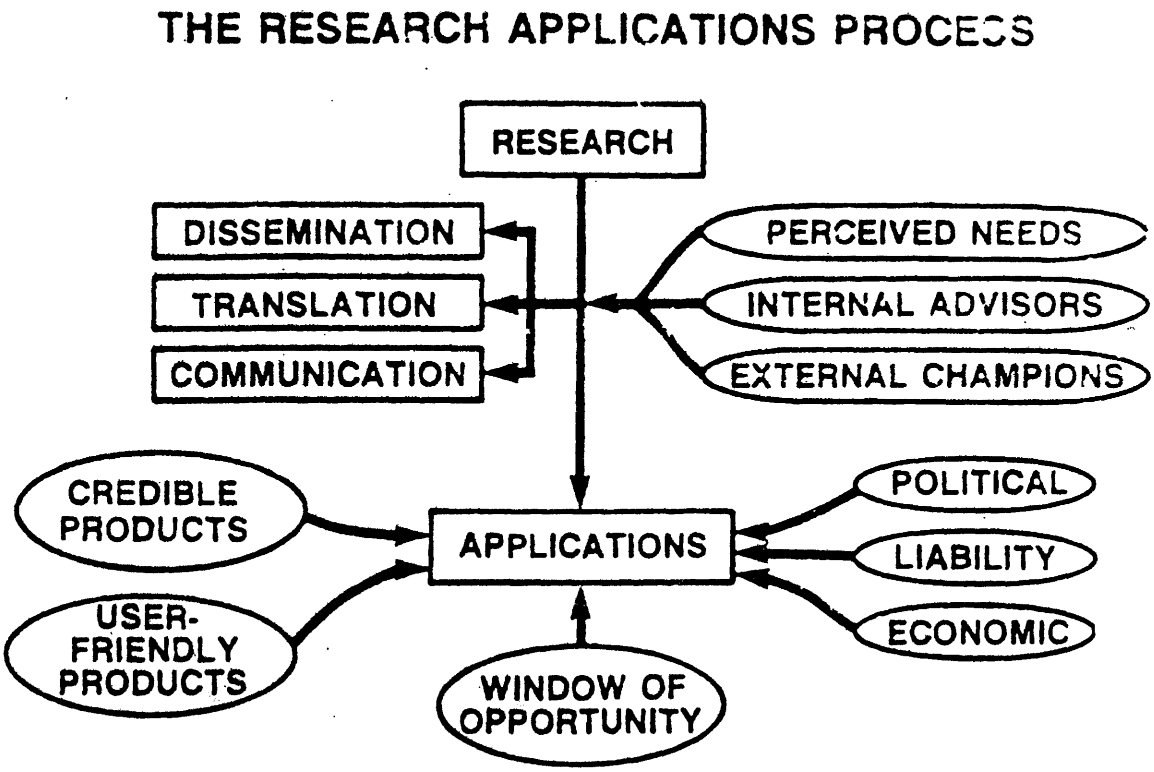


Figure 2:--Schematic illustration of factors contributing to the success of the research applications process. The two most significant factors that lead to success in the long term are activities that: a) produce champions of earthquake hazard mitigation and b) give them a goal or cause to work for in collaboration with other champions.

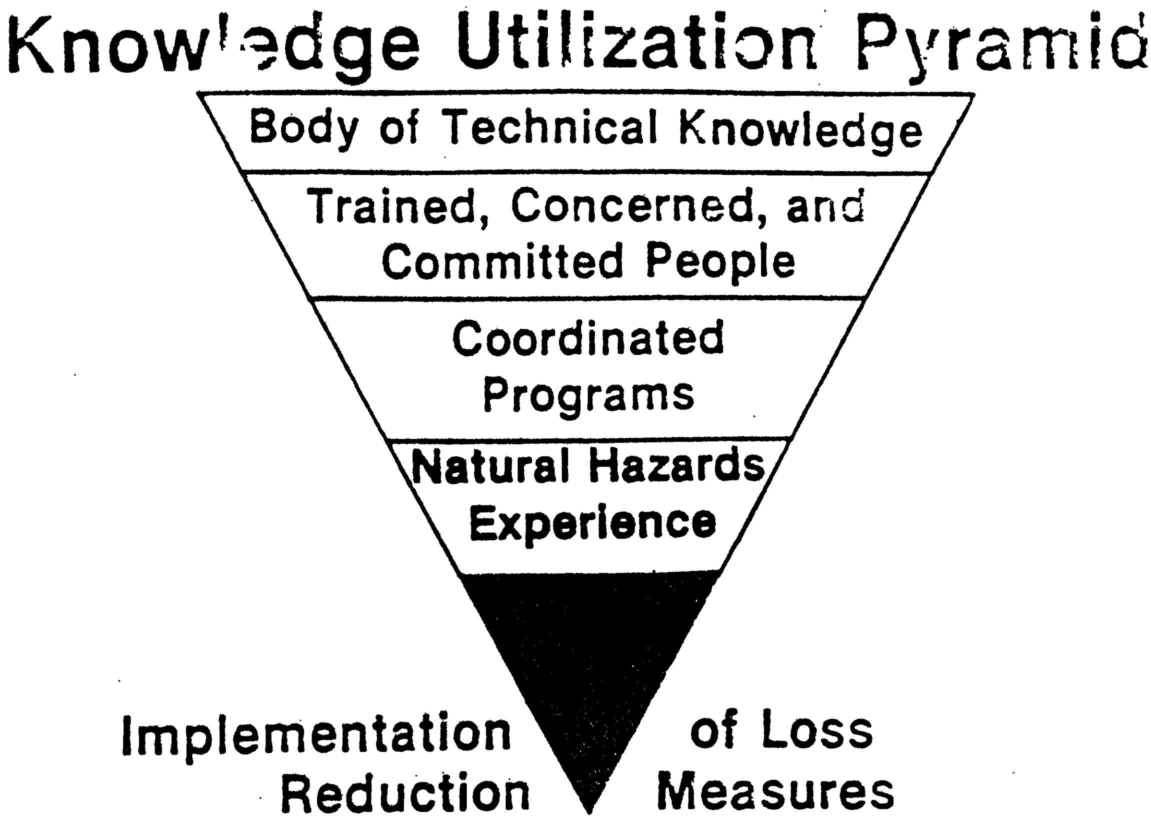


Figure 3.--Schematic illustration of the knowledge utilization pyramid. The gamble throughout the nation is whether implementation of loss-reduction measures will happen before the damaging earthquake strikes.

GROUND SHAKING HAZARD

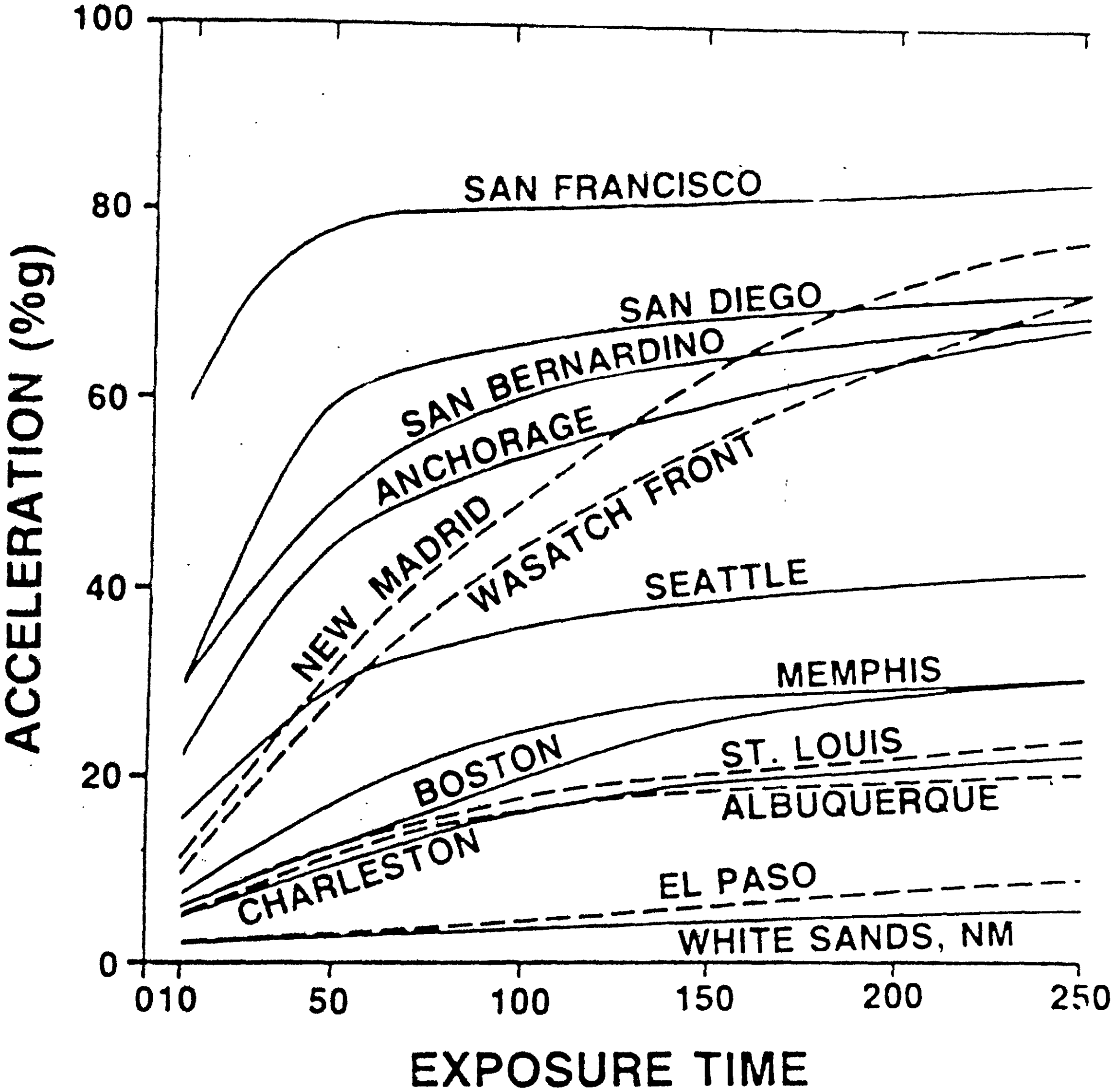


Figure 4.--Graph showing a comparison of the ground shaking hazard in the conterminous United states. Preparation of the maps from which these hazard curves were derived required the collaboration of several hundred researchers and practitioners over a period of 15 years. (Source: S. T. Algermissen, and others, 1982, U.S. Geological Survey Open-File Report 82-1033).

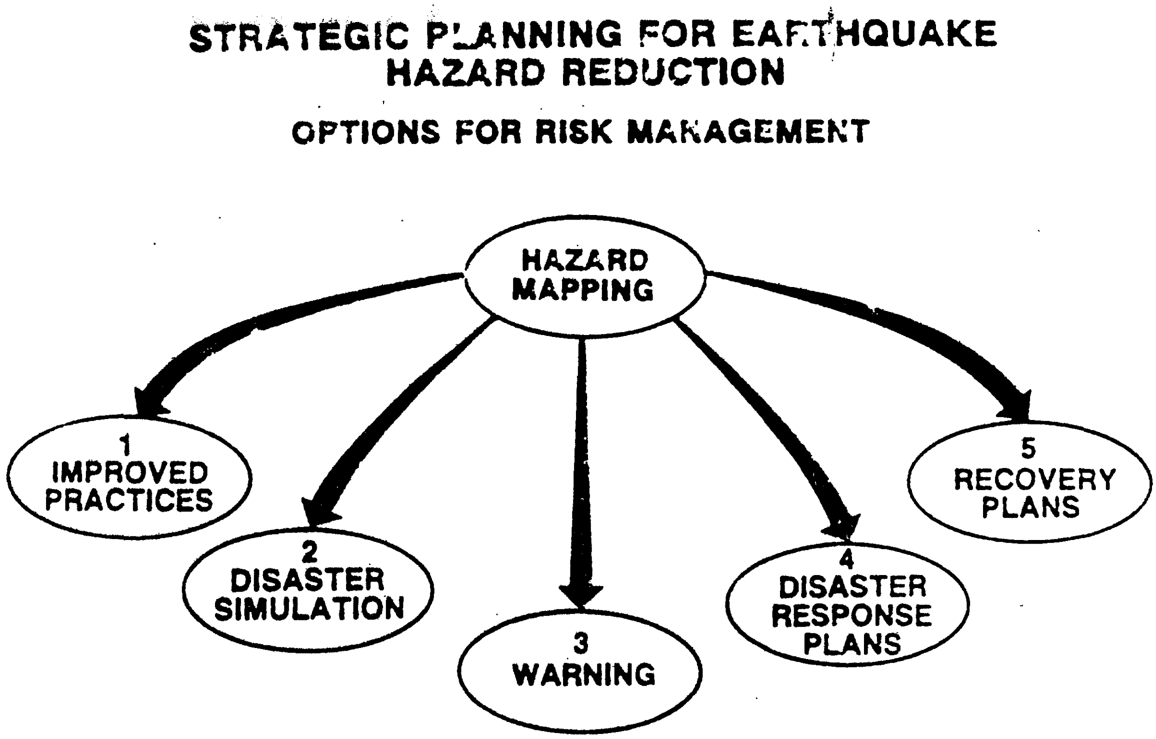


Figure 5.--Practitioners use maps of the ground-shaking hazard, an essential first step in many applications of knowledge, to devise the earthquake hazard mitigation measures.

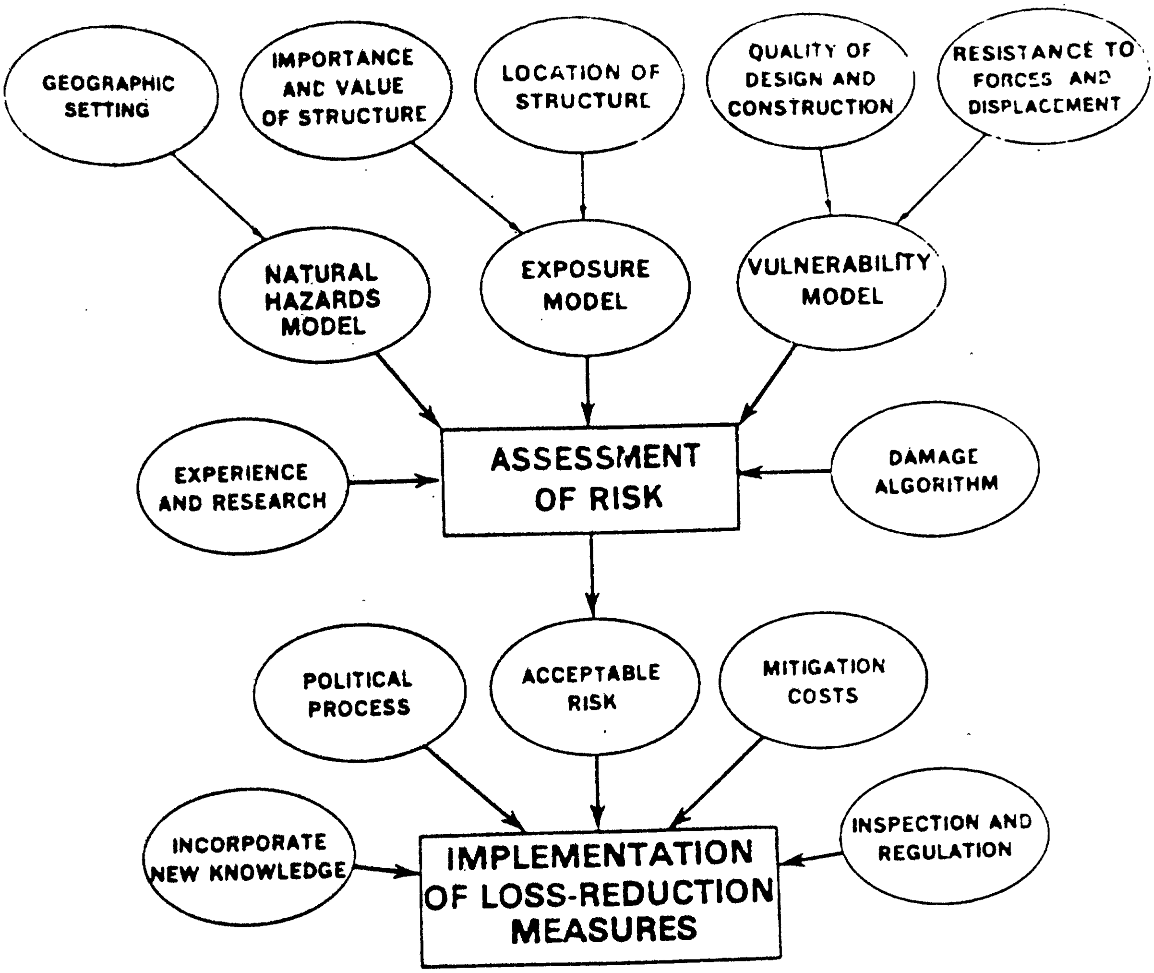


Figure 6.--Schematic illustration of important topics that researchers and practitioners must deal with in order to foster earthquake hazard mitigation (after Petak and Atkisson, 1983).

Differences in the perspective of scientists-engineers and decisionmakers (from Szanton, 1981).

ATTRIBUTES	PERSPECTIVES	
	SCIENTIST/ENGINEER	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 thought	Inductive, generic	Deductive, particular
5. Most valued outcome	Original insight	Reliable solution
6. Mode of expression	Abstruse, qualified	Simple, absolute
7. Preferred form of conclusion	Multiple possibilities with uncertainties emphasized	One "best" solution with uncertainties submerged.

Szanton, Peter, 1981, Not Well Advised: Russell Sage Foundation and Ford Foundation, 81 p.

Figure 7.--Differences in the perspectives of researchers (typified by scientists and engineers) and practitioners (typified by "decisionmakers") (after Szanton, 1981).

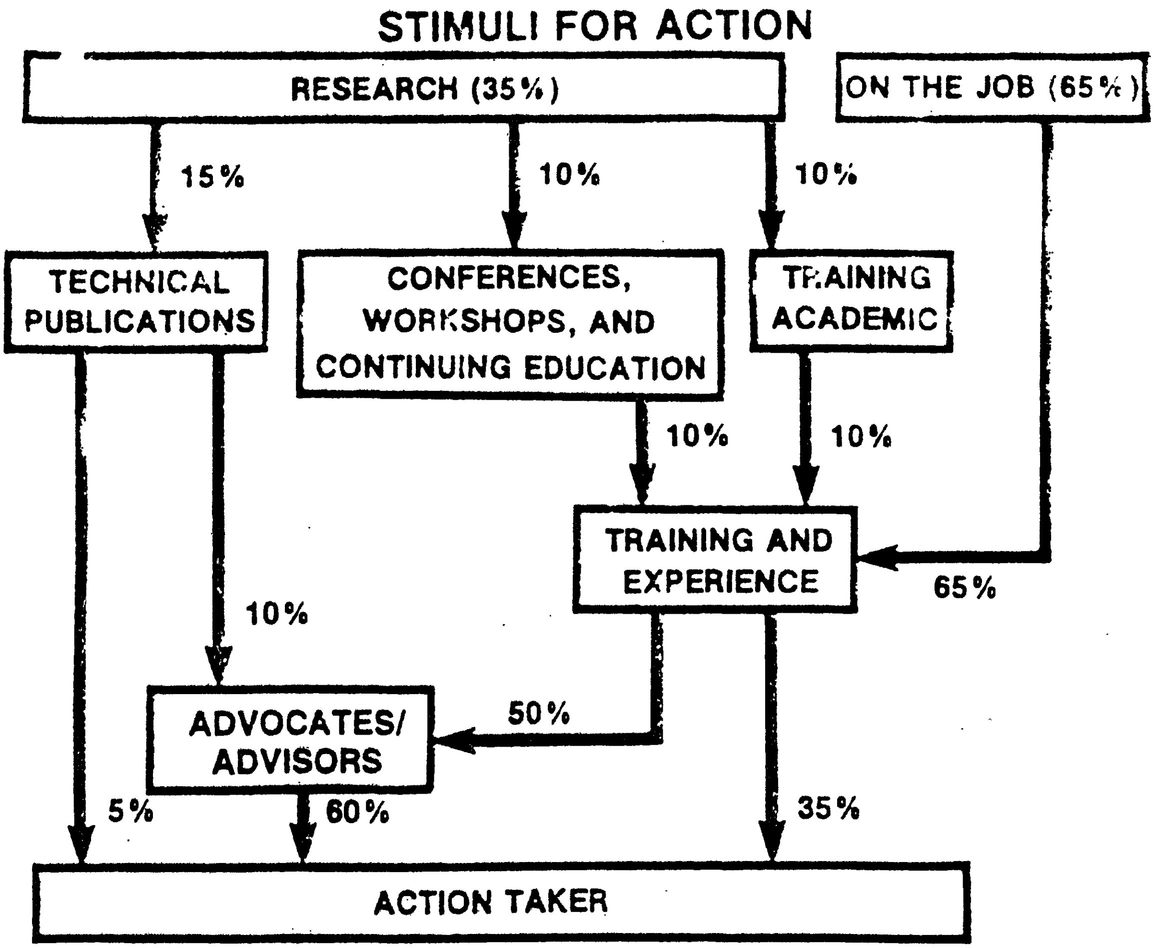


Figure 8.--Schematic illustration showing the relative importance of various external influences on an action taker. The influence of on-the-job training, workshops, experience, and advocates/advisors is very high; whereas, that of mailing publications is very low (from Thiel, 1988).

COMMUNICATION OF HAZARDS AND RISK INFORMATION

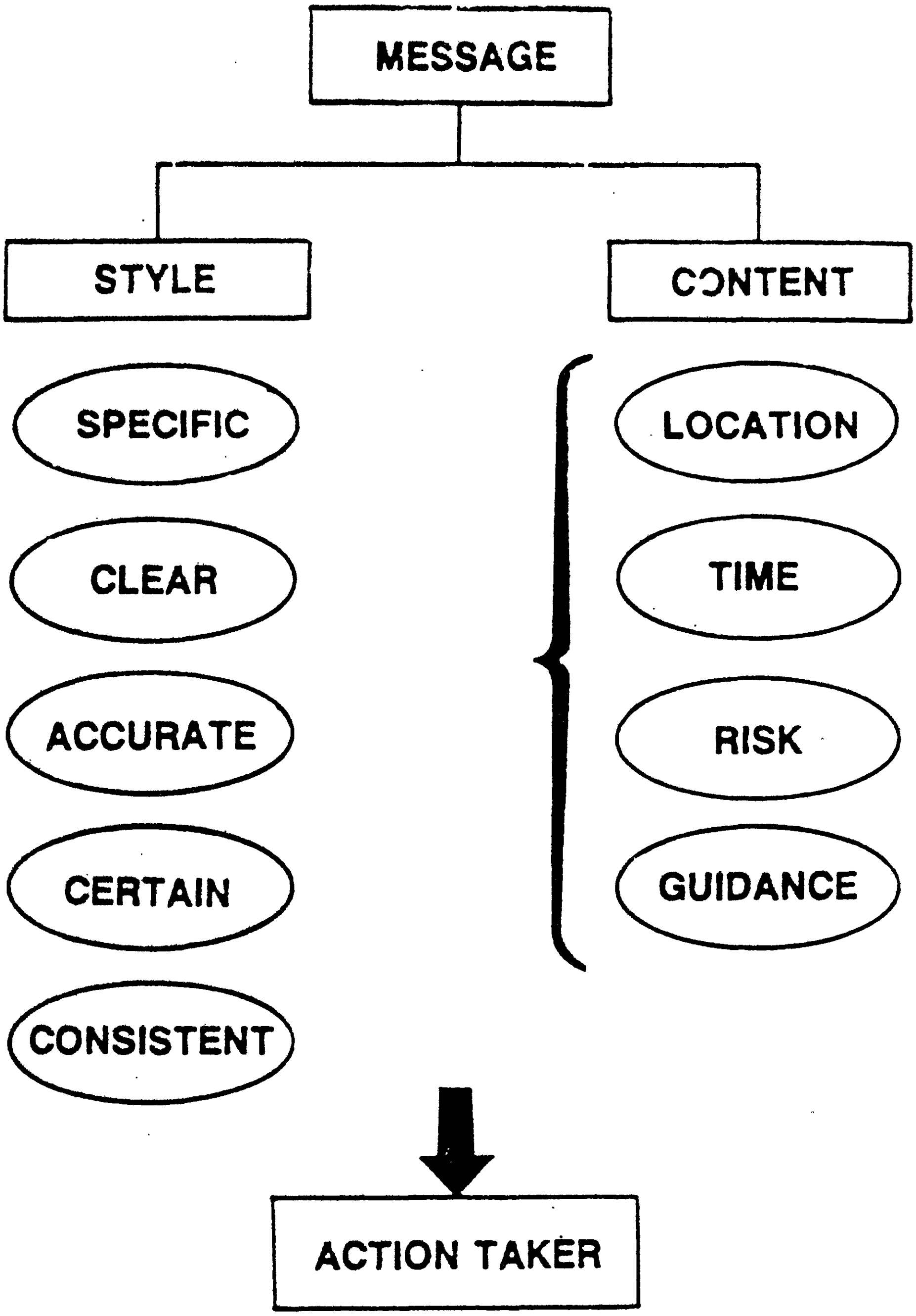


Figure 9.--Schematic illustration showing the essential characteristics of a well designed message to communicate earthquake hazards and risk information (after Mileti, 1987).

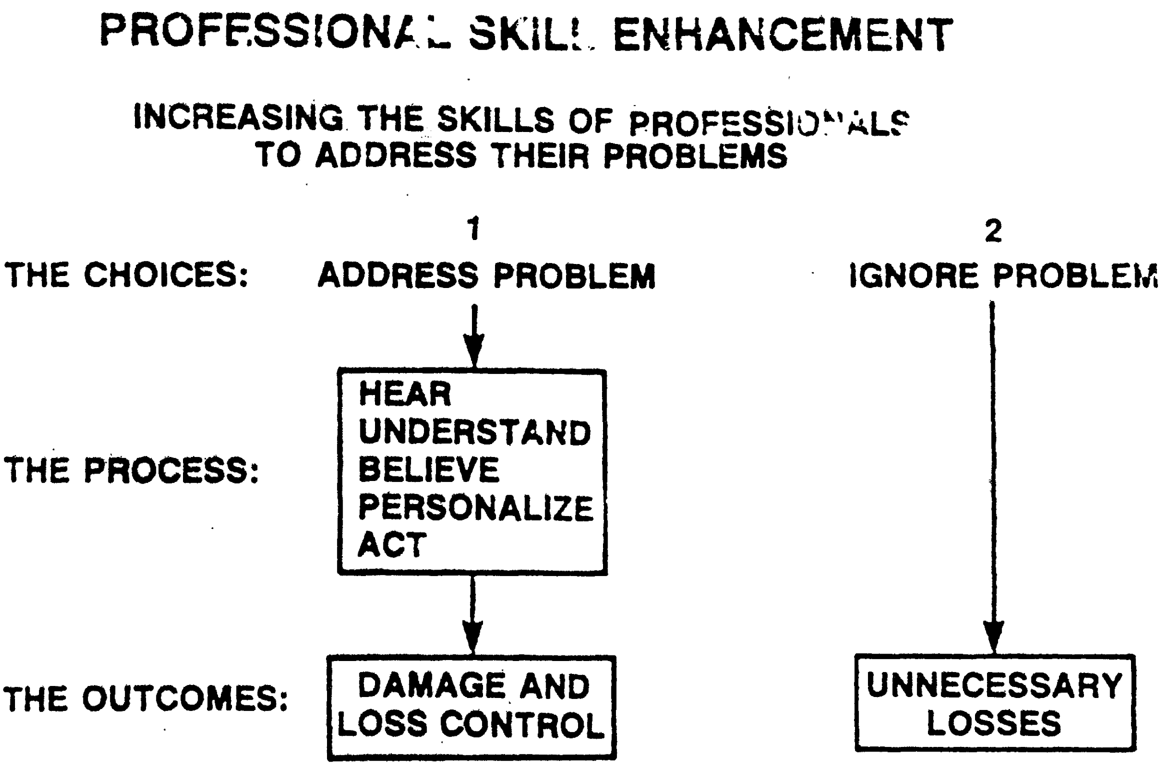


Figure 10.--Schematic illustration showing the basic process of professional skill enhancement.

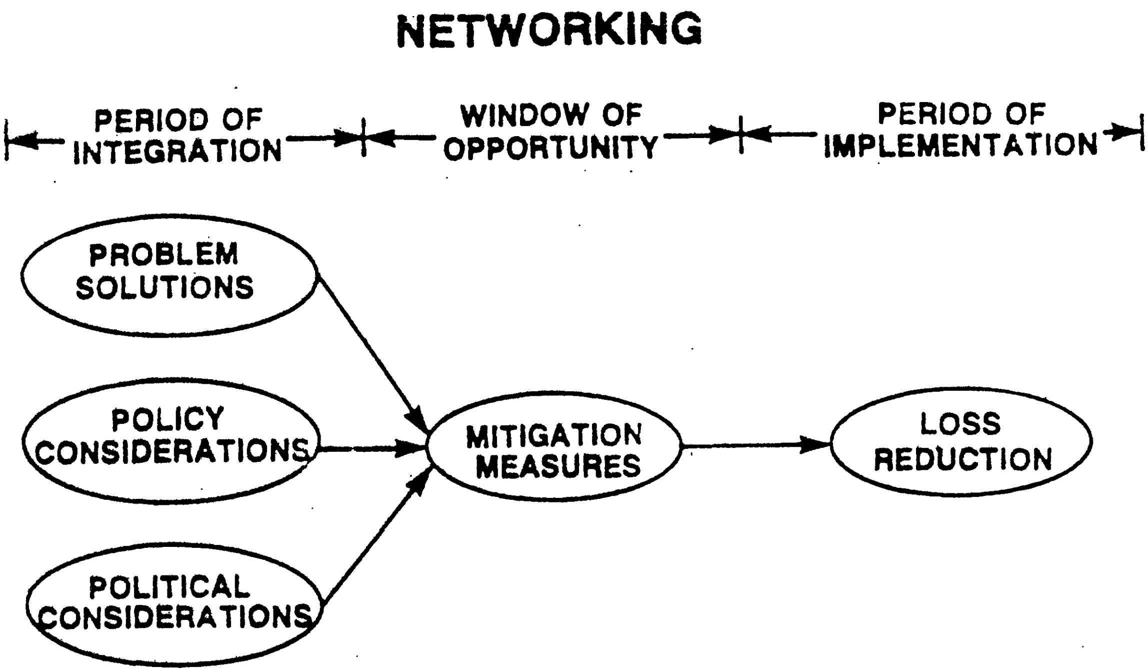


Figure 11.--Schematic illustration of the time-dependent flow of actions in the research applications process of the NEHRP. The first decade of the NEHRP has been characterized mainly as a period of integration in all states except California.

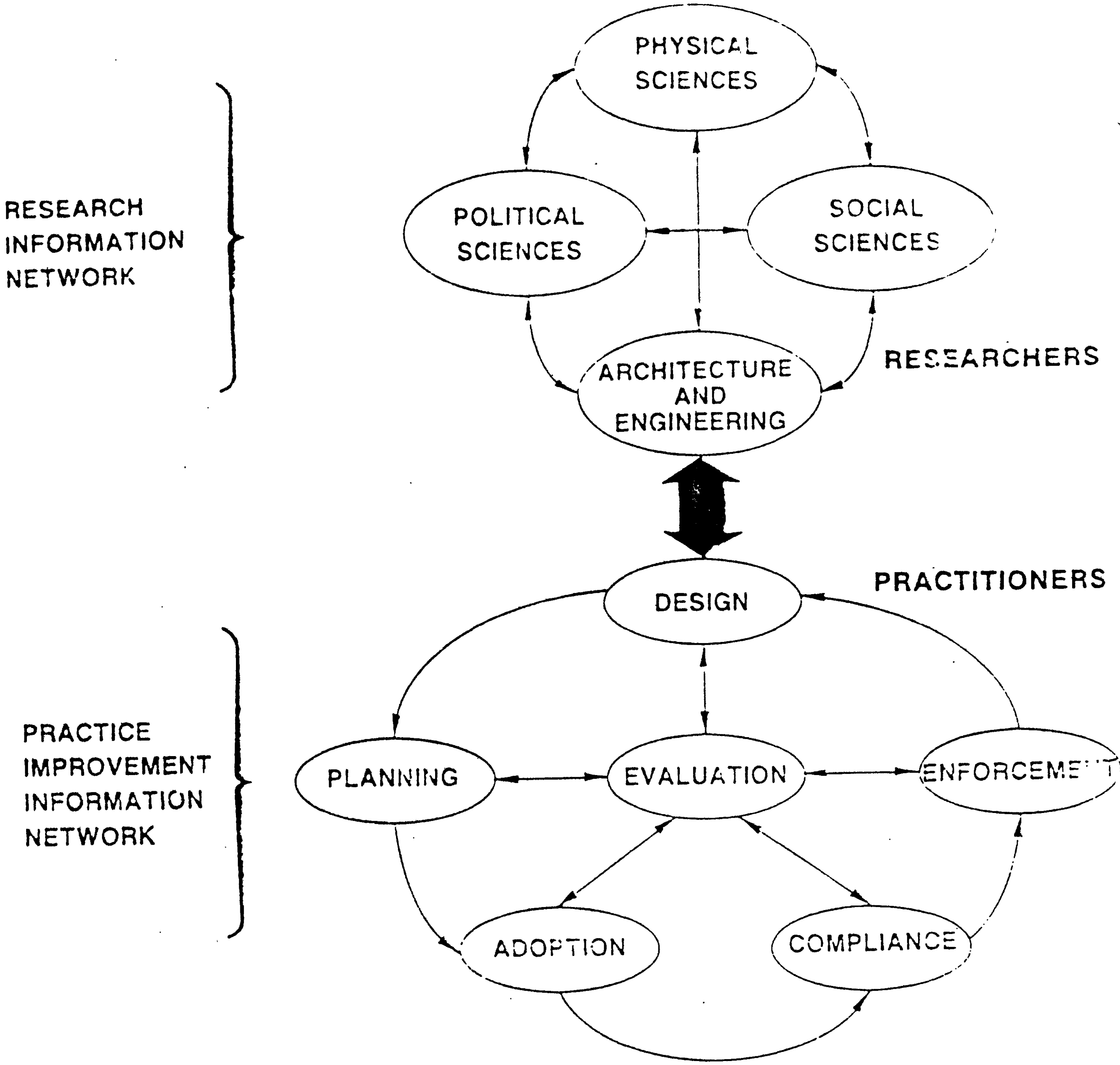


Figure 12.--Schematic illustration of collaboration between researchers and practitioners. In the first decade of the NEHRP, many researchers and practitioners exhibited a disdain for collaboration and limited ability to collaborate effectively. The key factor leading to earthquake hazard mitigation seems to be activities that: a) produce champions of earthquake hazard mitigation in each network, and b) give them a reason for collaboration. One deficiency of the research program is that very little research was performed to aid emergency medical response and disaster response operations.

IMPLEMENTATION OF LOSS REDUCTION MEASURES

By
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INTRODUCTION

Natural hazards such as floods, hurricanes, landslides, volcanic eruptions, tsunamis, wildfires, and earthquakes cause annual losses of about $10 billion in the United States. These hazards strike urban centers with little or no warning and cause great physical and societal impacts over a broad geographic region within a few seconds to a few days unless adequate preparedness and mitigation measures are in place. An urban center must start the implementation process long before the damaging event strikes. This process is very difficult. It can take a decade or more for a community to adopt and enact an implementation plan.

A community must develop safety policies and an implementation plan and political process to deal with each hazard. For earthquakes, the political process must deal with issues affecting physical development. They include:

- Hazardous Buildings.
- Essential and Critical Facilities (those parts of a community's infrastructure that must remain operational after an earthquake).
- High Occupany Buildings.
- Non-structural Hazards.
- Hazardous Materials.
- Rebuilding.
- Fault Rupture.
- Ground Failure.
- Ground Shaking.
- Flood Hazards.

IMPLEMENTATION

Implementation requires a long-term commitment. The first step of the implementation process occurs in a period of integration when problem solutions are brought together with policy and political considerations. Mitigation measures are the result. These measures must be implemented to achieve loss reduction. Usually a window of opportunity is provided by the occurrence of a damaging event. Such an event will often accelerate the implementation process by marshalling political and funding support.

Loss reduction does not happen unless policy is translated into actions.

Most implementing methods are derived from local government's corporate and police powers.

The implementing methods should be:

- o selected carefully,
- o adapted to local needs,
- o carried out as an integral program of complementary and mutually reinforcing actions, and
- o consistent with the general plan of the community.

One common obstacle in implementation is that:

- o Policies are usually the creation of the planning staff

  BUT

- o Responsibility for actions often rests with others.

  For example, the building department enforces building codes, the public works department carries out the strengthening of public facilities, and the fire department conducts safety inspections of commercial and industrial buildings. All actors are needed.

A successful implementation program requires extraordinary cooperation!!

A realistic goal of every community is to do those things that reduce the potential for damage **BEFORE** a damaging event strikes. There are three basic choices. They are to focus on:

- o Physical development issues,
- o emergency response issues, or
- o recovery issues.

PHYSICAL DEVELOPMENT

Physical development issues involve actions that lessen the damage to physical elements in a community which will reduce the requirement for emergency response and recovery.

There are ten physical development issues in every community that are critically important in reducing losses from earthquake hazards. They are:

- o Fault Rupture.
- o Ground Shaking.
- o Ground Failure.
- o Flood Hazards.
- o Hazardous Materials.
- o High-Occupancy Buildings.
- o Hazardous Buildings.
- o Critical Facilities.
- o Non-structural Hazards.
- o Rebuilding (i.e., Pre-Earthquake Planning for Post-Earthquake Reconstruction--PEPPER).

The first step in moving from policy to action is to clarify the hazard and to identify options for reducing it. Subsequent steps flow from this step, as noted below for each physical development issue.

FAULT RUPTURE - In the Central Mississippi Valley area, faults and seismogenic zones are difficult (but not impossible) to characterize because, unlike the San Andreas fault zone in California, they are buried two to three miles beneath the surface. The New Madrid seismic zone, which was the source of four great earthquakes in the winter of 1811-1812, is best known. It was defined on the basis of seismicity, gravity, magnetic, and geologic data. Surface fault rupture is common in the Western United States but unknown in the Eastern United States.

Implementation

Step One: Identify fault zones.
Step Two: Adopt guidelines and regulations for fault studies.
Step Three: Adopt land-use policies and regulations.

GROUND SHAKING - On the basis of a hypothetical intensity map for 1811 size earthquakes, ground shaking from a repeat of the 1811-1812 earthquakes in the New Madrid seismic zone would cause devastating effects throughout the Mississippi Valley area. The seven state area would experience strong ground shaking and physical effects (in terms of modified Mercalli intensity) that range from VII (architectural damage and ground failure) to X (severe structural damage (with collapses) and ground failure).

Implementation

Step One: Identify areas expected to experience strong shaking.
Step Two: Train plan reviewer.
Step Three: Train building inspectors.
Step Four: Review plans and inspect buildings for seismic resistance.

GROUND FAILURE - Strong ground shaking in an earthquake can trigger extensive landsliding and liquefaction over a wide area.

Implementation

Step One: Identify areas subject to ground failure.
Step Two: Review development plans for geotechnical concerns.
Step Three: Adopt subdivision regulations.
Step Four: Zone.
Step Five: Enforce through building permits and inspection.

FLOOD HAZARD - Strong ground shaking can cause dam failure and flooding. Design criteria for earth dams were evaluated and improved throughout the Nation following the 1971 San Fernando earthquake.

Implementation

Step One: Identif flood-hazard areas.
Step Two: Restrict uses in inundation areas.
Step Three: Adopt design standards for dams.
Step Four: Prepare evacuation plans.

HAZARDOUS MATERIALS - Every city has hazardous materials of some type. For example, tanks storing petroleum products can rupture during strong ground shaking or as a result of ground failure.

Implementation

Step One: Locate and identify hazardous materials.
Step Two: Require reinforcement of buildings, storage tanks, and equipment considered deficient.
Step Three: Adopt zoning regulations to restric use and storage of specified materials.
Step Four: Prepare evacuation plans.

HIGH OCCUPANCY BUILDINGS - It is clearly best to avoid siting high occupancy buildings in active fault zones. The potential effects of strong ground shaking and ground failure must also be evaluated for high occupancy buildings and appropriate steps taken to reduce the risk.

Implementation

Step One: Identify high occupancy buildings.
Step Two: Strengthen deficient buildings.
Step Three: Reduce occupancy in substandard buildings.
Step Four: Prepare evacuation plans.

HAZARDOUS BUILDINGS - The Nation has numerous unreinforced masonry buildings which have a high collapse-hazard potential in earthquakes.

Implementation

Step One: Locate and assess hazardous buildings (also critical facilities can be done at the same time).
Step Two: Adopt standards for reinforcement and time limits for compliance.
Step Three: Notify and educate building owner.
Step Four: Develop assistance programs.

NON-STRUCTURAL HAZARDS - Earthquake ground shaking can disrupt interior contents, even in a moderate-magnitude earthquake. Nonstructural damage can be expensive as well as the cause of deaths and injuries.

Implementation

Step One: Identify non-structural problems.
Step Two: Adopt local ordinances to reduce hazard.
Step Three: Develop public information program.

ESSENTIAL AND CRITICAL FACILITIES - Essential facilities (e.g., schools) may or may not require specific design criteria. However, siting, design, and construction of critical facilities such as nuclear power plants must satisfy a rigorous regulatory process. The goal is to ensure adequate margins of safety in a major earthquake for essential and critical facilities which must remain operational.

Implementation

Step One: Locate essential and critical facilities and assess their vulnerability.
Step Two: Enact and enforce performance standards.
Step Three: Strengthen, relocate, or replace critical facilities when standards cannot be met.
Step Four: Plan redundancy.

REBUILDING (Note: Pre-Event Planning for Post-Event Reconstruction.) - An old city exposed to the potential physical effects of a repeat of the magnitude 6.3, 1895 Charleston, Missouri earthquake or the great 1811-1812 earthquakes, can benefit from pre-event planning for post-event reconstruction. Such planning should evaluate factors such as the performance and potential vulnerability of high-occupancy buildings, unreinforced masonry buildings, and critical and essential facilities. Remedial measures can then be planned and implemented before the event strikes.

Implementation

Step One: BEFORE the earthquake strikes, identify high risk areas likely to require rebuilding.
Step Two: Establish reconstruction authorities and procedures.
Step Three: Assess damage potential now; plan for assessment immediately after earthquake.
Step Four: Adopt codes now for repair of damaged buildings.

Any community that implements loss-reduction measures to deal with these ten physical development issues will be less vulnerable to an earthquake disaster.

EMERGENCY RESPONSE

Every community needs to develop an emergency response capability in order to save lives and protect property. The issues include:

- Assess the hazards and risk.
- Plan for disaster response.
- Identify resources for response.
- Establish survivable communication systems.
- Develop capability for search and rescue.
- Plan for multijurisdictional response.
- Establish and train a response organization.

HAZARD AND RISK ASSESSMENT - Community leaders need to know what to expect in a damaging event.

Implementation

Step One: Identify potential ground shaking, permanent ground displacement, and other physical effects of an earthquake.
Step Two: Identify structures and facilities that are potentially vulnerable.
Step Three: Determine potential losses and socioeconomic impacts.
Step Four: Coordinate assessments with neighboring cities and counties.

PLAN FOR DISASTER RESPONSE - The plan is important, but the process that produces the plan is more important to the community when the event strikes.

Implementation

Step One: Evaluate existing plans for completeness with respect to responding to a damaging earthquake.
Step Two: Prepare a multihazard functional plan.
Step Three: Using a team approach, describe functions, responsibilities, and resources needed to respond to an earthquake.
Step Four: Obtain political commitment and funding to carry out the response functions.

IDENTIFY RESOURCES - The objective is to bring the right resources together at the right time to meet the need in the community.

Implementation

Step One: Identify resources needed to carry out each emergency response function.
Step Two: Inventory available resources.
Step Three: Assign responsibilities for working with all Government, public, and private sectors.

SURVIVABLE COMMUNICATION SYSTEMS - A community must have working communication systems after the event strikes.

Implementation

Step One: Identify public and private communication systems, capabilities, and services.
Step Two: Assess potential damage to communication systems.
Step Three: Take steps to upgrade systems, strengthen equipment, and develop backup capability.
Step Four: Secure essential service telephone capability.
Step Five: Decide how to inform all sectors of the public

after an earthquake.

SEARCH AND RESCUE - A community must prepare for the unthinkable--search and resuce after a damaging event knocks down some buildings.

Implementation

Step One: Identify high-occupancy structures that could collapse in an earthquake.
Step Two: Inventory equipment (cranes, bulldozers, concrete saws and cutters, acoustical listening devices, masks, gloves, etc.).
Step Three: Identify skilled personnel.
Step Four: Develop plan for search and rescue and assign responsibilities.
Step Five: Train and exercise.

PLAN FOR MULTIJURISDICTIONAL RESPONSE - A community must look at the "big picture" as well as the small picture within the boundaries of the community.

Implementation

Step One: Identify resources and services coming from inside and outside the jurisdiction.
Step Two: Estimate impact of an earthquake on internal and external resources and services.
Step Three: Develop daytime and nightime scenarios.
Step Four: Resolve regional issues such as public information, casualties, injuries, recovery of transportation systems, and displaced persons.

TRAINING - The competitive advantage in a disaster comes from training performed before the disaster.

Implementation

Step One: Identify training needs of the response organization--a team consisting of police, fire, public works, medical, and others.
Step Two: Establish and task a training committee to develop a training program meeting the needs of the response organization.
Step Three: Schedule, convene, and evaluate training workshops.
Step Four: Exercise the response plan and the response organization on simulated earthquakes.

RECOVERY

The primary goal of a community after a damaging event strikes is to restore everything to normal. The issues include:

- Restoration of services.
- Assessment of damage.

- Inspection and posting of unsafe buildings.
- Removal of debris.
- Short-term recovery program.
- Long-term recovery program.

RESTORATION OF SERVICES - The needs of the affected populace dictate the initial actions during the recovery period.

Implementation

Step One: Identify the providers of essential services inside and outside the community as a part of the overall response plan.
Step Two: Prepare to start repairs immediately.
Step Three: Work with other public and private agencies to establish priorities for restoration of services.
Step Four: Take steps to prevent further service disruptions.

ASSESSMENT OF DAMAGE - Community leaders need to know the nature and extent of the damage. Federal assistance depends on this activity.

Implementation

Step One: Identify skilled personnel who can conduct state-of-the-art damage assessments for public facilities.
Step Two: Prepare pubic works personnel and building officials for their roles in documentation.
Step Three: Improve initial estimates of damage.
Step Four: Work with Federal and State officials responsible for providing aid.

INSPECTION AND POSTING OF UNSAFE BUILDINGS - Safety is the primary issue. Rapid, high quality inspections are priority one.

Implementation

Step One: Identify training needs of building officials who have responsibility for evaluation of damaged buildings.
Step Two: Provide training to meet needs of building officials.
Step Three: Identify specific structures for post-earthquake inspection.
Step Four: Resolve issues of responsiblity for inspectors.
Step Five: Plan to post all inspected buildings with red, yellow, and green tags, using external personnel as needed.

REMOVAL OF DEBRIS - When 9-story buildings become 9 foot high piles of rubble, the normal operations of a community are significantly impacted, as well as the response operations. The rubble has to go as quickly as possible.

Implementation

Step One: Identify locations expected to have need for debris removal and the people and equipment required for the task.
Step Two: Coordinate debris-removal planning with search-and-rescue operations.
Step Three: Assign responsibilities in terms of an ongoing need due to aftershocks and demolition.
Step Four: Identify disposal sites.
Step Five: Anticipate and resolve issues concerning private property.

ESTABLISH PROGRAM FOR SHORT-TERM RECOVERY - Time is a critical factor during the initial recovery period. The high-pressure demand on decisionmakers is extraordinarily high.

Implementation

Step One: Identify the decisions that will be made in first few days to facilitate the short-term recovery of Government services, business, and housing.
Step Two: Establish authority for decisionmaking.
Step Three: Plan a system to administer the flood of applications to repair and rebuild.
Step Four: Assist businesses to plan for recovery needs.
Step Five: Plan for temporary housing needs.
Step Six: Plan to publicize the recovery plans, regulations, and services.

PRE-PLAN LONG-TERM RECOVERY - Although the pressure on decisionmakers lessens with time as "normalcy" is restored, the community leaders still need the best possible long-term recovery program. They have a unique opportunity to correct difficiencies.

Implementation

Step One: Identify the options for changing community design during the recovery period at the locations expected to experience severe physical effects and/or losses.
Step Two: Identify rebuilding problems in high-risk areas and the opportunities to change land use or occupancy.
Step Three: Develop conceptual plans for rebuilding.
Step Four: Establish reconstruction authority.
Step Five: Prepare reconstruction plan.
Step Six: Coordinate with adjacent jurisdictions.

SUMMARY

A community can lessen its vulnerability to natural hazards by implementing loss-reduction measures. The choices are:

- o Addressing existing physical development issues.
- o Developing emergency response capability.
- o Preparing for recovery.

A wide variety of actions can be accomplished under existing corporate and police powers of the community.

EARTHQUAKE LOSS REDUCTION BY LEGISLATION
Gaining the Adoption of Seismic Building Codes & Other Mitigation Measures In Your State

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After the Lisbon earthquake in 1755 when 20,000 people died beneath the rubble of collapsed masonry, the philosopher and naturalist, Rousseau, commented that, "If everyone lived out of doors, no one would be hurt by earthquakes." His point was correct, but his solution not acceptable. In general, it is true. "Quakes don't kill; Buildings do."

The greatest threat to life and limb from earthquakes is not nature, but the failure of man's built environment. Earthquakes produce ground shaking and various sorts of ground failure, but in and of themselves, these usually do not pose dangers of a serious nature to people. Most earthquake casualties are the consequence of collapsing buildings, falling bridges, failing dams, and other hazards posed by human constructions.

This means that whereas human beings cannot yet prevent nor control the forces of nature that cause earthquakes, it is within our power to prevent or reduce the damages. Due to the intensive research in earthquake engineering over the past twenty years, we can now construct buildings, bridges, and dams that will not fail during earthquakes, and we know how to construct them economically. Earthquake design doesn't cost. It pays. And it pays well, not only in terms of reduced property losses, but it especially pays in terms of reduced fatalities and injuries.

A Tale of Two Governments

The proof of this could hardly be more dramatically illustrated than by the recent experiences of California on October 17, 1989, and Armenia on December 7, 1988. Both experienced earthquakes of similar magnitudes, 7.1 and 6.9 respectively. Both occurred in regions of similar geologic and seismic domains. Both had similar population densities. And yet their outcomes could hardly be more dissimilar. Armenia's loss: Well over 25,000 dead and more than $16 billion in property. California's loss: Only 67 dead and $7 billion in property.

This dramatic difference was not a simple case of good luck on the part of Californians and bad luck on the part of the Soviets. Luck had nothing to do with it. The difference was the direct result of California's decades of earthquake engineering and preparation and of the Soviet government's almost total lack of such engineering and planning. If Candlestick Stadium in San Francisco had been built by Armenian standards, it would have collapsed, killing 30,000 or more. Because of the engineering and construction methods of American builders, there was not even one injury even though more than 60,000 people were packed into that structure for the World Series during that earthquake.

California's dramatic success in this recent earthquake is a direct consequence of many pieces of legislation passed in that state over the last 50-60 years. Some of these regulations are local, but the most important seismic regulations are statutes of the state. They have building codes for new buildings, for dams, for trailers, for utilities, for bridges, for existing buildings, for liquid and gas storage tanks and pipelines, for just about anything that could pose a risk to people. There are regulations for land-use planning as well. Furthermore, the entire populace has been prepared and trained in what to do before, during and after an earthquake. This education is through the schools, through the yellow pages of California phone books, through public service announcements on TV, through community sponsored programs, and a myriad of other means. Even shopping bags in some California grocery stores carry useful earthquake safety information printed on their sides. California has also, for many years, been gearing up and refining its earthquake disaster response capabilities. The fire departments, the police, the hospitals, the emergency response officials at all levels are trained and ready.

How Ready is the Midwest?

Following the recent Loma Prieta Earthquake in October, amidst the demands of fallen bridges, collapsed interstates, and destroyed buildings, California was so ready that it did not even exhaust its own resources to meet the needs of its people. Federal assistance was there, but the State could have handled everything by its own resources, so well prepared they were.

Not so in the Midwest. Statistically, the New Madrid Fault poses to the Midwest about the same probability of a damaging earthquake, 6.5 to 7.5 in magnitude, as exists today for Los Angeles. Only one midwestern state has a statewide seismic building code--Kentucky. The Indiana legislature adopted a code effective in 20 counties of the state just this last April, 1989. Earthquake education among the public is just beginning. All of the central United States have earthquake disaster response plans in various stages and levels of perfection and some of them are developed to a high level of sophistication.

But response planning, alone, is not the answer. Being ready for an earthquake means that your schools, hospitals, utilities, dams, bridges, and other constructions are built or braced to withstand earthquake forces. Until every state in the midwest has suitable building standards, we cannot say we are ready regardless of how sophisticated our response plans may be.

Not only are legislated building standards and seismic land-use planning lacking in the midwest, the greatest immediate threats to life are the existing buildings. There are more than 140,000 unreinforced masonry buildings in St. Louis, alone. There are, perhaps, 400,000 such structures within 150 miles of the New Madrid Fault. A 7.6 magnitude earthquake would probably damage most of them and cause the collapse of 1,500 or more. A collapsed masonry building leaves few survivors. In Missouri there are 2,200 schools and only one, just completed last year, is known to be seismically designed. Almost all are brick or concrete block construction, many two and three stories tall.

With respect to Midwestern bridges, only a few constructed in the last decade are built to withstand earthquakes. There are only four I know of - one on the Missouri River at St. Charles, Missouri; and three over the Mississippi at Cairo, Illinois; Caruthersville, Missouri; and Memphis, Tennessee. All others could fail.

On a scale of 100 for earthquake readiness: California would rate 90%. Armenia a zero. and the Midwest a 10%. One could argue and stretch that to 20 or 30%, but by anyone's objective analysis, the truth is that the state of earthquake preparedness in the central United States leaves much to do. The important point is that if we act promptly, we may have time to take appropriate measures to reduce the risk from midwestern earthquakes. California's loss can serve to be our gain if we heed the warning and take action now.

The Necessity of Both Mitigation & Response

Response planning and training is essential in preparing for earthquake disasters. But when it comes to reducing earthquake losses, response programs won't do it. Mitigation programs will.

Mitigation is a word that means "to reduce the severity of." Mitigation consists of things done _before_ a disaster that either prevent it or greatly reduce its losses and impact.

Response consists of things you do _after_ a disaster. If you do a good job of mitigation, the need for response will be greatly reduced and, in some cases, entirely eliminated.

For example, because of California's mitigation programs in the form of legislated regulations and building codes, very few buildings collapsed or were damaged sufficiently to pose any risk to people. Hence, California did not have to respond to 25,000 dead, 100,000 people injured, miles of fallen freeway, hundreds of impassable bridges, thousands of collapsed buildings, and millions of gallons of hazardous materials spilled into the bay. All this and more could have happened. But because they mitigated against all these catastrophes, what actually happened was but a mere whisper of what they would have had if they not been so ready.

The key was mitigation _beforehand_, not response _after the fact_. I do not mean to imply that response planning is unnecessary or unimportant. It is essential. But not coupling response planning with a mitigation program is shortsighted. What level of response would have been required to save Armenia after its earthquake? No level of response would have saved the 25,000 who died during those terrible fifteen seconds of shaking. The U.S. sent a rescue team to Armenia at great expense. After several nights days effort, they only saved two people. Neither can response effort reduce the $16 billion in building losses in Armenia. Only mitigation can do that.

Taking the First Steps in the Midwest

California is 50 years ahead of the midwest in earthquake readiness. We cannot expect to reach a level of seismic preparedness appropriate to our region in a short time. Neither do we have 50 years to do it either. What needs to be done?

California's regulations cover a spectrum of issues in earthquake safety. Their codes were adopted in stages over time. We must follow a similar approach, but hopefully compressed into a shorter time span than half a century. Eventually, in an ideal situation, there should be standards for new buildings and constructions as well as for old and existing ones. These codes mitigate against collapse and catastrophic failure. They legislate a "life safety" standard, not a "building preservation" standard. In other words, the engineering is intended to prevent collapse, not damage. To build against damage is too expensive and too high a standard except in the case of critical industrial facilities, like nuclear plants, which must maintain their integrity no matter what.

Therefore, the first step is to adopt a suitable building code statewide. It is not sufficient for a state to delegate the adoptions of such codes to county or municipal governments. They must be instigated and enforced from a level higher than local.

An illustration of why local option does not work was presented recently in Jonesboro, Arkansas. Arkansas has no statewide seismic codes. Jonesboro, a moderate sized university city, had enacted the first and only seismic building code in the state. Jonesboro is only a few miles from the southern end of the New Madrid Fault. A company who wanted to build a small factory in the area approached the Jonesboro city council and requested them to repeal their seismic code. The facility would have employed less than a hundred people. The company representative said they would not build the plant in Jonesboro unless the seismic regulations were removed. On October 16, 1989, the city council repealed the code. On October 17, 1989, the Loma Prieta Earthquake occurred in California. The city is fortunate that the quake happened in California, this time, and not on the New Madrid Fault. The point is that with local option, any influential and misinformed developer can potentially nullify the code.

Such developers (and city councilmen) are uninformed because the basis of the argument against seismic codes is that they will add too much to the cost of building. This is not true. The structural part of a building is a relatively small portion of the total construction cost--usually amounting to less than 20% of the total. The increase in cost ranges from zero to 5%. Sometimes a simple adjustment in design will serve to make a building seismically designed with no added cost. Nevertheless, because of such misunderstandings, codes are repealed or do not pass at all.

How do Seismic Codes Gain Legislative Approval?

How do you get seismic building codes passed in your state? Several things have to come together. We know this from California's experience. We stand to learn from both their successes and their mistakes.

One would think that California's first seismic building codes would date back to 1906 when San Francisco experienced a devastating earthquake 8.3 on the Richter scale. This was not the case. The city was destroyed to a great extent by fires induced by the earthquake and which burned out of control for several days due to the fact that the water system had been destroyed and the fire department was unable to respond effectively. However, the commercially minded leaders of the city were afraid that to admit of an earthquake threat in their area because they thought it would be bad for business and tourism. For years it was believed, based upon information released by the city's leaders, that only 500 died in the quake, almost all by fire. We now know that perhaps 2,000 or more died, largely due to collapsed and damaged buildings, before the fire spread. In any event, what got immediate action was the revision of fire-fighting methods and instead of a seismic building code, they adopted a higher standard for resisting horizontal forces in buildings from wind. A building to stand wind forces is also somewhat better able to stand earthquake forces, but a wind code is not the same as a seismic one. The effects of strong wind and strong ground vibrations on a building are just not the same.

In 1925 a damaging earthquake occurred near Santa Barbara which stimulated the passage of a weak building code for California, but it was not enforced and had little effect.

In 1933 Long Beach experienced a devastating earthquake in which 80% if the schools of the city collapsed. This immediately prompted the passage of the Field Act which, among other things, specifically required seismic standards for schools. Fortunately, the Long Beach earthquake happened outside of school hours and so few were hurt in school buildings. In Armenia, more than 12,000 of those killed were Soviet school buildings. It will take a generation for Armenia to recover from this preventable calamity.

The 1933 Long Beach earthquake marked the very first real seismic building codes in California. The Riley Act, another seismic building code statute, was also passed in 1933, and the former act passed in 1925 with the Santa Barbara Earthquake, began finally to be enforced.

However, the state of earthquake engineering was in its infancy and the building codes were weak. Enforcement was also lacking.

In 1971, the San Fernando earthquake did a billion dollars in damages and caused some fatalities. The Van Norman dam underwent partial liquefaction and came within inches of failing. Had it been breached, some 20,000 lives would probably been lost in residential developments down stream. Several hospitals also were damaged beyond repair, including one that collapsed. The Olive View Hospital had been built to the most recent seismic code specifications. It opened in 1970 and was damaged beyond repair less than a year later. The San Fernando earthquake did much to stimulate revisions in seismic codes and to cause the passing of many other regulations pertaining to seismic safety to include not only structural engineering, but architecture and other non-structural provisions.

It can be said that California did not really have effective seismic building codes until after 1971, some 38 years after Long Beach and some 65 years after the Great San Francisco Quake. But even in the 1970s, enforcement was imperfect.

Even into the 1980s, there were still school buildings that did not comply with the state construction laws. Only after a threat by the state's Attorney General to hold local school officials and local school boards personally liable did California's schools finally come into 100% compliance.

The point is that it takes time to pass good seismic legislation and even after it is passed, it takes time to accomplish full compliance. Without statewide legislation, adequate seismic building practices will not take place. Legislation without adequate enforcement mechanisms will not work.

So How Do We Get Seismic Coded in Our State?

Legislators make the laws. In order for them to act intelligently and responsibly, they must be educated accurately and well. They must be convinced of the reality of the risk. Their knowledge must be clear and accurate. They must also understand clearly what the phrase, "seismic building code," means as well as what it does not mean. To accomplish this requires a lot of effort on the part of a lot of educated people with a commitment to the cause. Among these people must be leadership of either a group or of an individual or individuals. In addition, a climate of public acceptance for such legislation must also exist. Legislators are sensitive to the attitudes of their constituents. Without public receptivity, one cannot expect legislative receptivity.

Here are the steps toward positive Legislative action toward beneficial seismic regulations. I will first list them and then discuss them.

1. The public must provide a climate of receptivity to hearing about earthquake risk and to seeing something constructive done about it.

2. Legislators and the governor must become convinced of the reality of the risk and be moved to consider doing something about it.

3. Legislators and the governor must understand what kinds of legislation are effective and in what order they should be prioritized.

4. To achieve this, leadership must come forward and become a "policy entrepreneur" willing to carry the ball into the end zone.

5. Nature must provide a window of opportunity by causing an earthquake of sufficient interest to the state to make its citizens and leaders become ready for action.

Let us now discuss each of these five areas in greater detail.

A Climate of Public Receptivity

People will be receptive to earthquake legislation and regulation if they are well aware of the risk. This comes by educational campaigns originating from emergency management agencies and universities. The Federal Emergency Management Agency (FEMA) has provided funds to states at seismic risk for years to contribute toward public awareness. FEMA has also produced numerous excellent publications on almost every aspect of earthquake preparedness and mitigation. These are free. A list of these is provided at the end of this article.

The public must be raised from a level of awareness to preparedness. The first step to making the public aware of an earthquake problem is easily compared to motivating the public to do something about it. It is easy to inform a million people that they should strap their water heaters to the wall and see that their frame houses are firmly bolted to their foundations. But out of a million who know this, how man=ny actually do it? This is a challenge to which no really good solution has yet to be devised. We are working on it at the Center for Earthquake Studies in Cape Girardeau. When we find a solution, we will share it with everyone.

If your state has an "earthquake information" center, then you have the mechanism for achieving public awareness. Such centers exist in the Eastern United State in Missouri, South Carolina, and Tennessee. A University campus is the ideal setting for such a center, It can be funded by state monies, supplements from FEMA funds that are already pouring into your state emergency management agencies on an annual basis. Bush centers respond to mail and telephone inquiries as well as provide speakers for civic organizations, churches, local governments, schools, hospitals, and other groups upon request. Such centers can also provide invaluable information and education to the news media.

Public awareness cannot be achieved without the cooperation of the media. It is imperative to see that your principal newspaper science writers and principal television news reporters are well informed with accurate information on earthquakes. The media is an essential element in public awareness. They must be integrated into the program as a part of the earthquake information team. You need earthquake experts who know seismology and earthquake engineering who can talk with the media in lay terms--accurate and yet understandable to the masses.

After awareness, comes the next level of public action which is preparedness or action. Knowledge never saved anyone in an earthquake. Only actions can do that. Hence, whereas an "earthquake information" center or an "earthquake information" program in your state will get people's attention, few beneficial effects will occur until building practices change, utilities and hospitals take non-structural measures, people "earthquake-proof" their homes and businesses, and school officials adopt earthquake safety programs and exercise them. The Center for EArthquake Studies in Cape Girardeau is actually the first "earthquake mitigation" center on a university campus in the country. In cooperation with the State Emergency Management Agency, it's task goes beyond information. Instead of waiting for people to write and call for information and responding to that, the Missouri program is one of aggressive action to see that all schools, hospitals, utilities, businesses, etc. are not only informed, but really ready. The Missouri program has taken initiative to see that legislators and top state government leaders are educated and accurately informed, instead of waiting for them to call first. It is an experiment, a marriage between the academic and the emergency management aspects of the state. Only time will tell if the marriage produces good offspring.

The important thing is that regardless of the means employed, without a level of public awareness of the earthquake risk, the legislators will not adopt seismic building codes. But public awareness isn't enough.

<u>Making Legislators & Governors Aware of the Risk</u>

Strategies for convincing legislators and executive officers of state government that there really is a seismic risk in your state and that something should be done about it are something you will have to tailor to your own state. Dealing with politicians is unavoidably a political activity, even though your intent is purely educational. There are protocols, hidden agendas, and all manner of things to deal with that are usually unfamiliar to educators. Nevertheless this bridge must be built and used.

The news media is an essential part of the process. The news media provides a bridge of communication between the experts who know about seismology, seismic risk, and earthquake engineering, and the politicians who need to have an understanding of such information is order to legislate responsibly.

The most important point is that for politicians, who will be the ones to ultimately enact the seismic legislation called for by the data, you must keep things simple, short, and accurate. This is difficult. You need experts who know the intricacies of science and statistics, but who can distill the essence of esoteric technicalities into understandable English and useable concepts that will lead to the desired legislation.

Furthermore, in dealing with earthquake risk, politicians and the public don't want to hear all of the behind the scenes debates that go on endlessly among scientist who are forever trying to refine a number here, reduce a standard deviation there, gain one more fact over there. A scientific investigation never stops. We can never learn everything there is to know about the New Madrid Fault or any other fault. Hence, every scientific publication that comes out is another "progress report" in a sense. Seismologists and engineers will always debate this point and that and they should. This is true science.

But for politicians and the public, all this debate is not only incomprehensible, but misleading. All they can use are "bottom line" data. Scientists can know among themselves that such "bottom Lines" are never final, but the public must be given information and numbers upon which they feel confident to act.

At a recent meeting of the United State Geological Survey in Memphis attended by many earthquake scientists throughout the Eastern U.S., the news media sat in on a debate among scientists as to what really are the probabilities of a damaging earthquake in the New Madrid Seismic Zone by the year 2000 and after. The disagreement among scientists caused some politicians in the state of Tennessee to say that perhaps they don't need to do anything at all about building codes and seismic preparedness until the scientists can make up their minds.

What needs to be stated unequivocally is that there is no question among scientists that the New Madrid Fault has produced massive earthquakes of damaging magnitudes and that it will do so again and again. We debate as to how big and when, but we all expect it to happen again. Here are some probabilities that are clear, simple, and in line with the geologic, historical, and instrumental data for the fault. You can quote these as being the result of several decades of research by a number of scientists and are the best data we now have. They are published in the Journal of Geophysical

Research, Vol. 90, 6737-6753, 1985. Dr. Arch Johnson and Susan Nava of the Center for Earthquake Research and Information, Memphis State University, are the authors. The following table is a summary of average values, plus the addition of interpolated statistics for a 7.1 magnitude event which was the size of the earthquake that happened October 17 in California.

*Earthquake Probabilities for the New Madrid Fault

Richter Magnitude	by the year 2000	by the year 2040
6.3	50%	90%
7.1	33%	67%
7.6	10%	25%
8.3	1%	3%

* as of 1989

These figures are simple, they are mean values, they are rounded, and they are well within the variety and range of figures currently published and accepted by seismologists. The 6.3 event is equal to the last damaging earthquake on the New Madrid Fault in 1895 which was centered near Charleston, Missouri, and Cairo, Illinois. A 6.3 event is what devastate Long Beach, California, in 1933. The 7.1 event is equal in magnitude to that which happened in California, October 17, 1989. The 7.6 corresponds to the maximum amount of energy currently thought to be stored up on the fault. The 8.3 event corresponds to the approximate magnitudes of the great shocks of 1811-12. A probability of 1-3% is saying that we don't expect this to happen in our lifetimes. All of the rest could happen in our lifetimes and should be prepared for.

So first convey to your political leaders a definitive, decisive set of earthquake risks for which they should be preparing. Maps of projected earthquake intensities for such events are also available to show which cities and counties are to be most effected in each of the central United States. Contact your state emergency or disaster agency for these.

A sheet summarizing facts about the New Madrid fault, including a map, is attached. We distribute this sheet by the thousands in Missouri. Feel free to adopt it for your state.

<u>Teaching Legislators About Seismic Legislation</u>

If legislators and/or their aides are not given good reliable information, they may draft bills for seismic provisions that are not as good as they could be. Furthermore, most objections to enacting seismic building codes are because of misunderstandings or misinformation about such provisions. Someone in your state has to take the initiative to see that your legislators will be making decisions based on correct and complete information. I have found in dealing with Missouri legislators that you need to address the following issues:

1. Statewide seismic building codes do not mean that every building in every state has to comply with the same building standard. Seismic building codes include zoning maps so that the higher risk areas build to a higher standard that the lower risk areas. Emphasize that the lowest or no risk areas will probably remain unaffected.

2. Seismic building codes already exist. A state does not have to develope them. All they need do is to adopt an existing code--the UBC, the BOCA, the NEHRP, the SSBC--all of these are the result of the input of hundreds of engineers and years of refinement. At some level they have all been tested with real earthquakes.

3. Seismic Building Codes contain exemptions. Typical ones are one and two family dwellings, agricultural structures, and buildings of low occupancy such as warehouses.

4. Seismic Building Provisions are not prohibitively expensive. The usual increase in construction costs is 1-5%. Sometimes, with an adjustment in architecture, a seismic design can result with no increased costs. consider that property owner will often spend thousands of dollars over the life of a building for fire and tornado. The additional cost of seismic design can be considered a one-time insurance premium good for the life of the building. It is a bargain when considered in these terms.

5. Seismic Building Codes do not apply to existing buildings. This is an important, but separate issue. Seismic building codes apply to newly constructed buildings. The retrofit of present structures is possible, but considerably more expensive that constructing a building to seismic design at the outset.

6. Seismic Building Codes are complex and an engineer or architect must have special training to put them to use. Some legislators will object to adopting seismic codes in their state because no engineers or architects in their state have been trained for seismic design. There are short courses available. In one week's intensive training, an engineer or architect can obtain the additional education they need to add this to their professional skills. If the state adopts seismic building codes, this will create a demand for such services from the building design community which they will quickly respond to meet.

7. Seismic Building Codes will not drive away business nor interfere with commerce, as is sometimes argued by seismic code opponents. Specific cases might be cited where particular enterprises did not locate in a particular area because of their erroneously perceived higher building costs, but in general other forces of the marketplace control the placing of business, not earthquakes. The two most financially and commercially

prosperous regions of the entire world are probably Japan and California, both of which rank with the top five or six most seismically active areas of the world. Both Japan and California have strong seismic building codes. Obviously, such codes have not interfered with their commercial growth in any measurable way.

B. Seismic Building Codes are better than property insurance. Some argue that if they have earthquake insurance, they don't have to worry whether or not their house, apartment or building is seismically designed. First of all, seismic design prevents building collapse and building collapse is the principal cause of death in an earthquake. Your insurance may restore your building, but it cannot restore your life. But more importantly, you must realize that earthquake insurance will not replace your damaged building as you may think. This is for several reasons. One possibility, if we really have a catastrophic earthquake, is that insurance claims will be so great the companies will be unable to pay. This is a real concern to insurance companies who have calculated that a great earthquake of magnitude 8.3 or larger in either the New Madrid Fault or the West Coast could produce property losses that would exceed the aggregate of all their reserves and assets. Another thing to consider are deductibles which are often substantial. Earthquake coverage also often has exemptions for chimneys, brick veneer, fire places, and other aspects of your house or buildings that are most likely to sustain damage. The best way to insure that your house or building or utility won't be lost to earthquake damage is to employ mitigation measures--both structural and non--structural. Then the damage won't happen and you won't need the insurance.

9. Some states have statutes that stipulate that anything legislated by the state has to be paid for by the state. Hence, if seismic building codes would place an extra burden of building inspection and/or enforcement upon local officials, the state must fund that extra burden. Sometimes this type of statute (which is present in Missouri) is used to argue against a statewide code. Obviously, this is no reason to avoid a state seismic code, but only a detail to work out. If the state mandates such a code, state funds should be allocated to carry them out. This has to be a part of the legislation. If a legislated code has no monetary appropriation to enforce it, it won't work.

10. The basic seismic building codes for a state must be legislated at the state level. Local option does not work. State legislators and executive officers know that if they propose state seismic building codes, or state codes of any kind, there will be opposition. Some try to dodge this opposition by promoting local regulation. "Let each city or county legislate their own regulations." This has never been shown to work for seismic building codes. Some seismic regulations concerning architecture, non-structural provisions, mobile home, land use planning, etc., can and should be locally adopted and enforced by local jurisdictions. But for structural integrity of buildings, bridges, dams, and other major constructions, this must be on a state level. Otherwise, your state will never have effective codes to protect its citizens.

A perfect example of why local codes do not work was provided recently in the Jonesboro, Arkansas, incident discussed earlier in this article.

The issue of whether or not seismic building codes should be a matter for state legislation or local touches upon one of the fundamental philosophies of government in the United States. Thomas Jefferson Said "the government that governs least, governs best." This is the so called "conservative" political point of view. While this principle calls for minimum government, it does not call for no government. When local jurisdictions get the job done, they should be allowed to do so. Leaving things up to locals is a valid principle when it works. In the case of seismic building codes, it does not work. If a state leaves it up to the locals, experience has long shown that very few locals will adopt, administrate and enforce such codes. Hence, if a state official wants to defer the "local option," it is the same as no codes at all for most communities, and even where cities or counties may adopt codes, they will rarely be effective. Seismic building codes is one of those areas where a higher level of government must step in or the job is not done.

You Need a Policy Entrepreneur

The history of seismic building code enactment in California, both on the state and the municipal levels, has shown that little will happen unless a single individual or group of individuals asserts leadership and initiative to get the right legislative actions accomplished. It doesn't take a highly trained seismologist or earthquake engineer to assume this role. An interested and informed citizen can do it, as was the case in some instances in California. An active task force appointed by the Governor can do it. But there must be direction and leadership that will commit to the task until done. That could be you.

You need an Earthquake

No one seems to worry about earthquakes, seriously, until one happens. Human natures is to be reactive rather than proactive. We all want to close the barn door after the horse is out, but always seem to find other things to do before the fact. This is a problem with earthquakes. After the quake, the damage has been done and can't be prevented. It took several earthquakes of major proportions in California to get Californians motivated enough to do what was necessary. They took over 50 years. We don't have 50 years in the Midwest.

However, an earthquake can be motivating to your state even when it does not happen in your state. THe Mexico Earthquake of 1985 was highly motivating to Californians who, after that event, further refined their mitigation programs which helped them to be really ready for the recent October 1989 event. Likewise, the California event has had a tremendously positive effect on the New Madrid to get ready for a Midwestern quake. California's loss can be our gain if we act effectively and soon.

Sociological research has shown that if you want to get appropriate seismic legislation into place, you need to do it within six months of an earthquake. We have, then, a six month window of opportunity. That means that if you want to take advantage of the window created by the Loma Prieta earthquake of October 17, 1989, you have until the end of April 1990. The first week of April, 1990, has been declared "National Earthquake Awareness Week." Use that event and the months preceding it to put into place those mitigation programs that your state needs.

Then, whatever does not get implemented into place, keep your plans ready for the next earthquake. If we had a magnitude 5.2 earthquake in the New Madrid zone that did a few thousand dollars worth of damage, not too much, but just a little--that would provide the spring board to put into place everything we need in the midwest to prepare for the really big one yet to come. Let's hope the New Madrid Fault gives us some time to prepare, a decade or more before the big one.

SUMMARY

In summary, the items needed to adopt suitable seismic legislation are listed below. When you have all of them, good things will happen in your state: Here they are in a few words:

1. Public receptivity
2. Convinced political leaders
3. Educated political leaders
4. A policy entrepreneur
5. An earthquake

The ideal strategy is to have ongoing programs for everything up to the last one, including draft bills waiting for an opportunity to be introduced. Then when a quake strikes anywhere in North America that draws interest from your state, make your move. When the opportunity strikes, you'll have six months to get the job done.

APPENDIX 1

EARTHQUAKE HAZARDS REDUCTION SERIES (EHRS)

July 1989

PUBLICATION NUMBER	TITLE	EHRS NUMBER
FEMA 67	Earthquake Public Information Materials: An Annotated Bibliography	EHRS # 8
FEMA 68	Earthquake Insurance: A Public Policy Dilemma	EHRS # 7
FEMA 69	Pilot Project for Earthquake Hazard Assessment	EHRS # 6
FEMA 70	Earthquake Preparedness Information for People with Disabilities	EHRS # 5
FEMA 71	Comprehensive Earthquake Preparedness Planning Guidelines: Corporate	EHRS # 4
FEMA 72	Comprehensive Earthquake Preparedness Planning Guidelines: County	EHRS # 3
FEMA 73	Comprehensive Earthquake Preparedness Planning Guidelines: City	EHRS # 2
FEMA 74	Reducing the Risks of Nonstructural Earthquake Damage: A Practical Guide	EHRS # 1
FEMA 75	Preparedness for People with Disabilities (Brochure)	EHRS # 9
FEMA 76	Preparedness in High-Rise Buildings (Brochure)	EHRS # 10
FEMA 77	The Planning Process (Brochure)	EHRS # 11
FEMA 87	Guidelines for Local Small Businesses	EHRS # 12
FEMA 83	Societal Implications: A Community Handbook	EHRS # 13
FEMA 84	Societal Implications: Selected Readings	EHRS # 14
FEMA 90	An Action Plan for Reducing Earthquake Hazards of Existing Buildings	EHRS # 16
FEMA 91	Proceedings: Workshop on Reducing Seismic Hazards of Existing Buildings	EHRS # 15
FEMA 95	NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings Part I: Provisions & Maps (1988 Edition)*	EHRS # 17
FEMA 96	NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings Part II: Commentary (1988 Edition)*	EHRS # 18
FEMA 99	Improving Seismic Safety of New Buildings: A Non-Technical Explanation of NEHRP Provisions	EHRS # 20
FEMA 98	Guidelines for Preparing Code Changes Based on the NEHRP Recommended Provisions	EHRS # 21
FEMA 140	Guide to Application of the NEHRP Recommended Provisions in Earthquake-Resistant Building Design	EHRS # 25
FEMA 111	A Guide to Marketing Earthquake Preparedness: Community Campaigns that Get Results	EHRS # 23
FEMA 112	Marketing Earthquake Preparedness: Community Campaigns that Get Results	EHRS # 24
L-143	Preparedness in Apartments and Mobile Homes	EHRS # 22
FEMA 135	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Water and Sewer	EHRS # 26
FEMA 136	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Transportation	EHRS # 27
FEMA 137	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Communications	EHRS # 28
FEMA 138	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Power	EHRS # 29
FEMA 139	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Gas and Liquid Fuels	EHRS # 30
FEMA 143	Abatement of Seismic Hazards to Lifelines: Proceedings of a Workshop on Development of an Action Plan - Papers on Political, Economic, Social, Legal, and Regulatory Issues	EHRS # 31
FEMA 142	Abatement of Seismic Hazards to Lifelines: An Action Plan	EHRS # 32
FEMA 146	Comprehensive Earthquake Preparedness Planning Guidelines: Large City	EHRS # 33
FEMA 149	Seismic Considerations Elementary and Secondary Schools	EHRS # 34
FEMA 150	Seismic Considerations Health Care Facilities	EHRS # 35
FEMA 151	Seismic Considerations Hotels and Motels	EHRS # 36
FEMA 152	Seismic Considerations Apartment Buildings	EHRS # 37
FEMA 153	Seismic Considerations Office Buildings	EHRS # 38
FEMA 154	Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook	EHRS # 41
FEMA 155	Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation	EHRS # 42
FEMA 156	Typical Costs for Seismic Rehabilitation of Existing Buildings Volume I - Summary	EHRS # 39
FEMA 157	Typical Costs for Seismic Rehabilitation of Existing Buildings Volume II - Supporting Documentation	EHRS # 40
FEMA 158	Earthquake Damaged Buildings: An Overview of Heavy Debris and Victim Extrication	EHRS # 43
FEMA 162	Differences between the 1985 and 1988 Editions of the NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings	EHRS # 44

PUBLICATION NUMBER	TITLE	EHRS NUMBER
FEMA 172	Techniques for Seismically Rehabilitating Existing Buildings (Preliminary)	EHRS # 49
FEMA 173	Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings, Supporting Report	EHRS # 46
FEMA 174	Establishing Programs and Priorities for the Seismic Rehabilitation of Buildings, A Handbook	EHRS # 45
FEMA 175	Seismic Evaluation of Existing Buildings: Supporting Documentation	EHRS # 48
FEMA 178	A Handbook for Seismic Evaluation of Existing Buildings (Preliminary)	EHRS # 47
FEMA 176	Estimating Losses from Future Earthquakes - Panel Report (A Non-Technical Summary)	EHRS # 50
FEMA 177	Estimating Losses from Future Earthquakes (Panel Report and Technical Background)	EHRS # 51

ADDITIONAL EARTHQUAKE PUBLICATIONS

FEMA 46	Earthquake Safety Checklist
FEMA 48	Coping with Children's Reactions To Earthquakes and Other Disasters
FEMA 66	Coping with Children's Reactions To Earthquakes and Other Disasters (Spanish)
FEMA 88	Guidebook for Developing a School Earthquake Safety Program
FEMA 113	Family Earthquake Safety Home Hazard Hunt and Drill
FEMA 159	Earthquakes: A Teacher's Package for K-6 Grades
L-111	Safety Tips for Earthquake
Poster #6	A Blueprint for Earthquake Survival

National Earthquake Hazards Reduction Program (NEHRP) Publications

National Earthquake Hazards Reduction Five Year Plan for 1989-1993
NEHRP/Commentary and Recommendations of the Expert Review Committee 1987
National Earthquake Hazards Reduction Program Fiscal Year Activities (Annual Report to Congress)

The publications are free of charge. Copies may be requested by writing to the following address:

Federal Emergency Management Agency
P.O. Box 70274
Washington, D.C. 20024

EARTHQUAKE HAZARDS REDUCTION SERIES

:NTER FOR EARTHQUAKE STUDIES

APPENDIX 2
David Stewart
Director
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Southeast
Missouri State University

ABOUT THE NEW MADRID FAULT

e New Madrid Fault System Extends 120 Miles Southward from the area of Charleston, Missouri, and Cairo, Illinois, through New Madrid and Caruthersville, following Interstate 55 to Blytheville and on down to Marked Tree, Arkansas. It crosses five state lines and cuts across the Mississippi River in three places and the Ohio River in two places.

e Fault is Active, Averaging More than 200 Measured Events per Year (1.0 or more on the Richter scale), about 20 per month. Tremors large enough to be felt (2.5-3.0 on the Richter scale) are noted annually. Every 18 months the fault releases a shock of 4.0 or more, capable of local minor damage. Magnitudes of 5.0 or greater occur about once per decade, can do significant damage, and be felt in several states.

e Highest Earthquake Risk in the United States outside the West Coast is along the New Madrid Fault. Damaging temblors are not as frequent as in California, but when they do occur, the destruction covers over more than 20 times the area because of underlying geology.

Damaging Earthquake in this Area, 6.0 or greater, reoccurs about every 80 years (the last one n 1895). There is a 50% chance of such a quake by the year 2000. The results would be erious damage to schools and masonry buildings from Memphis to St. Louis.

Major Earthquake in this Area, 7.5 or greater, happens every 200-300 years (the last one in 1812). There is a 10% chance of such a disaster by the year 2000 and a 25% chance by 2040. A New Madrid Fault rupture this size would be felt throughout half the United States and damage twenty states or more. Missouri alone could anticipate losses of at least $6 billion from such an event.

e Great New Madrid Earthquake of 1811-12 was actually a series of over 2000 shocks in five months, five of which were 8.0 or more in magnitude. Eighteen of these rang church bells on the Eastern seaboard. The very land itself was destroyed in the Missouri Bootheel, making it unfit even for farming for many years. It was the largest burst of seismic energy east of the Rocky Mountains in the history of the U.S. and was several times larger than the San Francisco quake of 1906.

en Will Another Great Earthquake Happen the Size of Those in 1811-12? Several lines of research suggest that the catastrophic upheavals like those in 1811-12 visit the New Madrid region every 500-600 years. Hence, emergency planners, engineers, and seismologists do not expect a repeat of the intensity of the 1811-12 series for at least 100 years or more. However, even though the chance is remote, experts assign a 1% probability for an 8.0 or greater event by the year 2000 and a 3% probability by the year 2040. Earthquake probabilities for known active faults always increase with time, because stresses within the earth slowly and inexorably mount, year by year, until the rocks can take no more, and a sudden rupture becomes inevitable.

MORE

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Our Greatest Concerns are the 6.0-7.6 Sized Events, which do have significant probabilities in the near future. A 6.0 shock has a 90% chance by the year 2040. Damaging earthquakes of this magnitude are a virtual certainty within the lifetimes of our children.

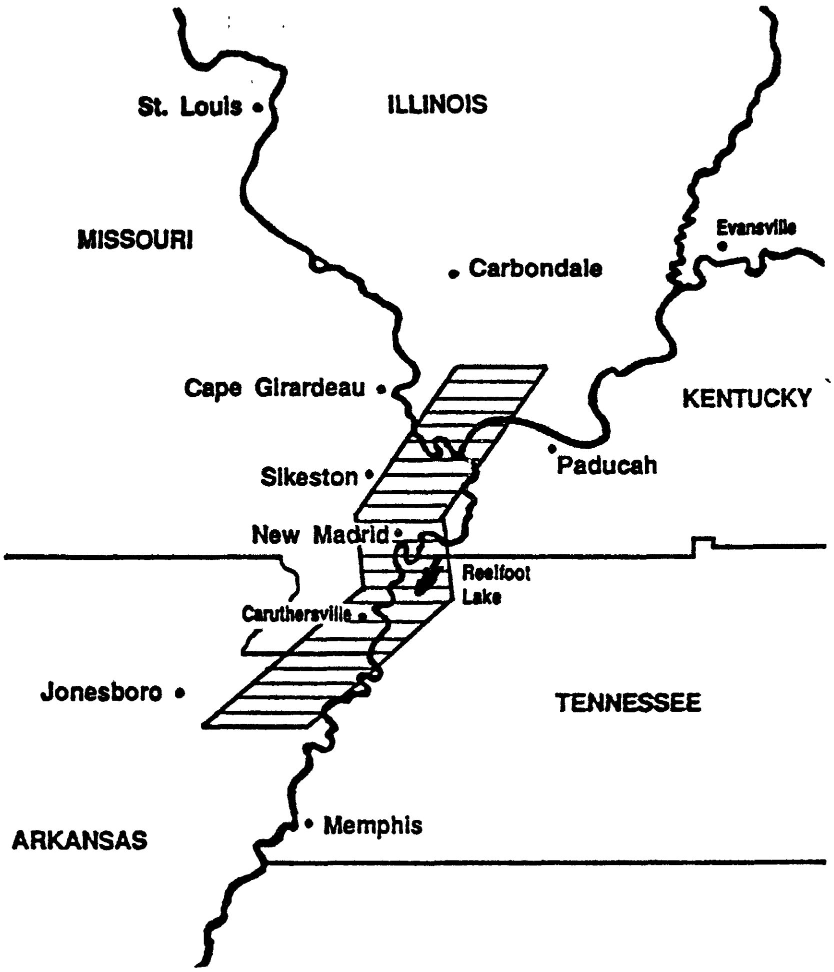
What Can Be Done to Protect Ourselves? Education, planning, proper building construction, and preparedness are proven means to minimize earthquake losses, deaths, and injuries. San Francisco and Armenia have both recently experienced 6.9 - 7.1 magnitude quakes. San Francisco was prepared; Aremia was not. San Francisco suffered 67 deaths and less than $7 billion in property losses. Armenia had over 25,000 deaths and lost more than $20 billion. Missouri and the Midwest are more prepared than Armenia, but only a fraction as prepared as San Francisco.

We have a choice. While we still have time, we can get ready and cut our losses, or we can do little or nothing and be caught unprepared. We cannot prevent the coming of an earthquake it will happen--but we can prevent it from being a major disaster. Write the Earthquake Center at Southeast for free literature on protecting yourself and your property.

What is the Richter Scale? The Richter scale of earthquake magnitude is a measure of the energy released at the source of an earthquake deep within the earth. It is determined by measuring the amplitudes of ground motion on seismographs. An earthquake has a fixed amount of energy and only one Richter magnitude.

How Much Increase in Energy Does Each Unit of the Richter Scale Represent?
It is incorrect to say that each unit of the Richter scale corresponds to a tenfold increase in energy. Each unit, say from 5.2 to 6.2, actually represents 31-32 times difference in energy release. Every two units represent 1,000 times more energy, and every two-tenths of a unit represents double the energy.

If a Fault Has Lots of Little Earthquakes, Will Larger Ones Be Prevented?
The answer is, "No". A magnitude 6.0 (which is damaging) is 1,000 times more energy than a 4.0 (which is not damaging). An 8.0 (which is devastating) is 1,000 times larger than a 6.0. In other words, a fault would have to have 1,000 4.0 event to prevent the occurrence of a single 6.0, or a million 4.0 events (1,000 times 1,000) to prevent a single 8.0.



MAP OF NEW MADRID FAULT

Exercises To Illustrate Some of the Political Judgments Made In The Implementation Of Loss-Reduction Measures

Although northern California was hit hard by the Loma Prieta earthquake, the disaster was much smaller than it might have been. The primary reasons were preparedness and building codes. The long term investments of communitites in northern California is these two types of actions during the past few decades paid off in a very small loss of life for such a devastating earthquake.

What Can Communities Do?

Decisionmaking to avoid or to reduce losses from earthquake hazards is restricted by economic, social, and public policy factors. The principal restraint is stated by the question, "How much will it cost?" If a community decides to attempt to reduce losses from earthquake hazards, its planners and decisionmakers must face the possibility of increased costs and decide what actions are conservative and prudent.

As communities accept the premise that costs associated with specific loss-reduction actions sluch as avoidance, land-use zoning, engineering design, and insurance are prudent, the question that will be asked is, "How much are we willing to pay?" An initial requirement for answering this question is for the community to determine.

- The physical causes of each natural hazard and the probability of each hazard occurring locally.
- The current local annual loss and the potential for suddenloss from each hazard.
- The local distribution of levels of relative severity expected from each hazard.
- The potential loss as a function of time and loss-reduction actions.

What Is the Benefit-Cost Ratio of Reducing Losses from Earthquake Hazards?

No widely accepted method exists for determining benefit-cost or risk-benefit ratios for specific loss-reduction actions. The following excerpt from **The Nature, Magnitude, and Costs of Geologic Hazards in California and Recommendations for Their Mitigation** (1973) provides some insight into benefit-cost analysis of the ground shaking hazard:

> Given a continuation of present conditions, it is estimated that losses due to earthquake shaking will total $21 billion (1970 dollars) in California between 1970 and 2000. Most of damage and loss of life will occur in zones of known high seismic activity; structures that do not comply with the Field and Riley Acts, passed in 1933, will be especially vulnerable. If the present-day techniques for reducing losses from earthquake shaking were applied to the fullest degree, life loss could be reduced up to 90 percent, the total value of losses could be reduced by as much as 50 percent. Total costs for performing the loss reduction work would be about 10 percent of the total project loss, which with 50 percent of effectiveness provides a benefit to cost ratio of 5:1.

1. "State tax monies are better spent on emergency management . . ."

2. "Seismic building codes will drive away business."

3. "There is disagreement among scientists about the seismic risk."

4. "If we appoint a task force of experts to develop codes for our state, the process will take years."

5. "We have no engineers or architects qualified to design for earthquakes."

6. "I don't wish to add any extra cost to my new home, for ultimately making homes unaffordable for everyone."

7. "I don't believe in statewide seismic codes."

8. "Seismic codes should be left to local communities and counties."

9. "Adoption of seismic building codes could put some farmers out of business."

10. "The people of our State cannot afford seismic building codes."

11. "With earthquake insurance, who needs seismic building codes."

12. "We cannot legislate statewide building codes without incurring costs for the local building inspectors as well."

Discussion Questions

Pretend you are a policy entrepreneur or concerned citizen who is taking some initiative to promote legislation to adopt suitable seismic provisions in your state. Consider the following statements that have been made by legislators and/or other government leaders who oppose such codes being legislated by the state. What would be your answer in each case? (Note that ever statement below contains fallacies and/or misstatements of fact. Your Assignment is to recognize the fallacy or misinformation and rebut the argument with a positive argument for state building code legislation.

1. "State tax monies are better spent on emergency management and developing better earthquake response plans, rather than on building codes and mitigation. The way to save lives in an earthquake is to have better response capabilities."

2. "Seismic building codes will add too much cost to construction and will drive away business."

3. "There is disagreement among scientists about the real level of seismic risk in our state and I think it has been way over blown. Why should we do anything until the scientists can agree. Maybe there won't be any earthquake at all. Maybe they all happened back in 1811-12 and there won't be any more."

4. "If we consider seismic building codes, we will have to appoint a task force of experts to develop such codes for our state. This could take years to accomplish."

5. "We have never had seismic codes in our state so far and there are no engineers or architects qualified to design for earthquakes. We need to train a bunch of professionals first and then consider adopting earthquake building codes. Otherwise we will have the cart before the horse."

6. "I sure don't want to add any cost to my new house with seismic design, which I don't think I need. What about all those other people who want to build a new home. If we have state codes, this may add so much cost they can't afford to build a home."

7. "I don't believe in statewide seismic codes. Why should the areas of no earthquake risk in our state have to build to the same construction standards as those at high risk? It doesn't make any sense to me for everyone to be required to build to the same standards throughout the state."

8. "I think things like seismic codes should be up to local communities and counties. What business has the state interfering with what local builders and local property owners ? If seismic design is important to protect people, local governments can require it."

9. "Why should a farmer have to build all his barns and agricultural buildings to seismic standards when people are rarely in them for any length of time. If we adopt seismic codes, it could put some farmers out of business."

10. "The people of our state cannot afford seismic building codes. If I had to retrofit my house and place of business to meet seismic requirements, I would go bankrupt."

11. "As long as you can buy earthquake insurance, who needs seismic buildings codes? Any losses you have will be covered?"

12. "In our state anything the state legislates the state has to pay for. Therefore, we cannot legislate statewide building codes in our state and require local building inspectors to enforce them.

Getting in Your Two Bits Worth

If any of these twelve arguments are used in your state against adopting state seismic codes, you can answer the legislators or other government officials who used them by mail or in person. You can also answer any public figure in the newspaper either by letters to the editor or by being interviewed in an article. we live in a country with freedom of speech, freedom of the press, and freedom to elect or not elect officials to government. As informed policy entrepreneur has a lot of ways to have beneficial influence on legislative and governmental decisions.