EARTHQUAKE HAZARD IN THE MEMPHIS, TENNESSEE, AREA

ARCH C. JOHNSTON and SUSAN J. NAVA

There is a difference to be marked between hazard and risk. The two are most easily distinguished by answering the question: Can the actions of people have any effect on the situation? Hazard cannot be lessened or increased but risk can. The earthquake hazard in Memphis, Tennessee, is an inheritance of geographic location and is due to the city's proximity to the New Madrid seismic zone; it cannot be changed by man. Earthquake risk is the immediate danger posed to the population and it can be substantially altered by a number of actions, most significantly, improved construction and siting of buildings. The purpose of this paper is to give a brief introduction to the seismic hazard in Memphis, Tennessee.

THE NEW MADRID SEISMIC ZONE

The New Madrid seismic zone is depicted in Figures 1 and 2. Figure 1 shows the instrumentally located epicenters for the past nine years; the main branches of the seismic zone are delineated by the concentrated pattern of epicenters within the small box of Figure 1. Figure 2 shows the relationship of the zone to Memphis and Shelby County and to the major critical facilities in the surrounding region. The generalized modified Mercalli isoseismals of Algermissen et al. (1983) are superimposed; the contours are estimated as combined effects of maximum magnitude events in the northern and southern portions of the zone. A single event would not produce these estimated intensities at all locations.

The New Madrid seismic zone is regarded by seismologists and disaster response planners as the most hazardous zone east of the Rocky Mountains (Johnston, 1982) There are three basic reasons for this estimation:

1. In the winter of 1811-1812, the zone produced three of the largest earthquakes known to have occurred in North America (M_S 8.5, 8.4, and 8.8) and hundreds of damaging aftershocks (Nuttli, 1983).
2. A major geological structure--an ancient crustal rift--has been identified through a decade of extensive research (McKeown and Pakiser, 1982). The rift underlies the shallow

---

The authors are members of the staff of the Tennessee Earthquake Information Center in Memphis. They developed this paper for presentation at BSSC meeting in Memphis on January 22, 1985.

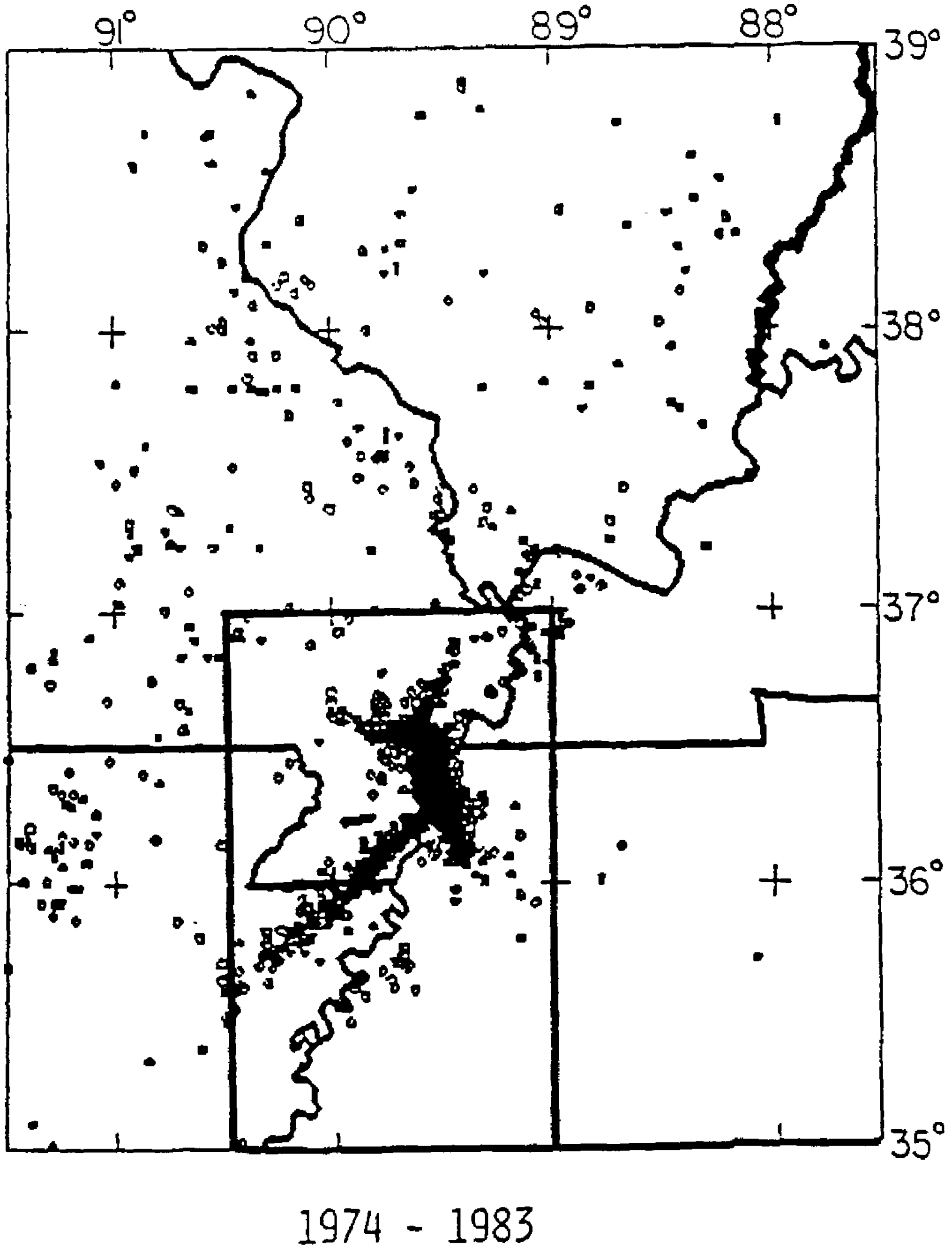

FIGURE 1 Map of the central United States with the 1974-1983 instrumental seismicity data set (Stauder and others, 1974-1983). The boundaries of the two source zones used for frequency-magnitude determination are: Large zones, 35.0 -37.0 N/89.0 -91.5 W.

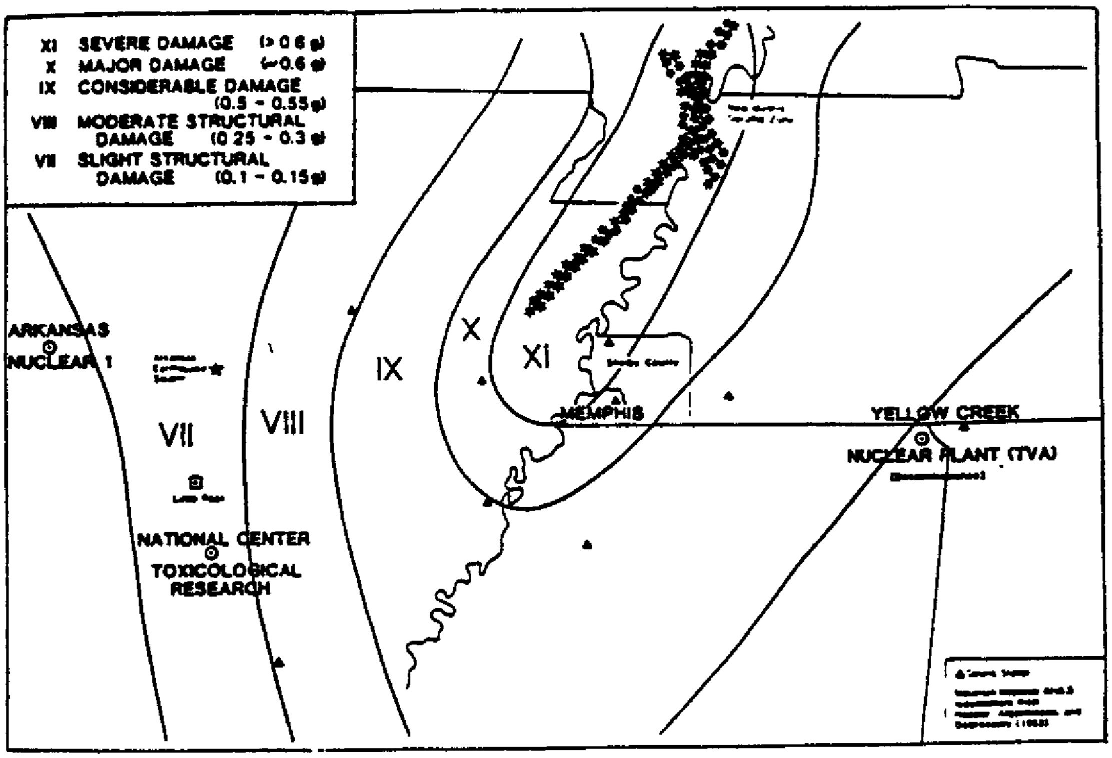

FIGURE 2 The relation of Memphis, Tennessee, and Shelby County to the New Madrid seismic zone. Also shown are major critical facilities in the region and Modified Mercalli isoseismals for a "composited" maximum magnitude New Madrid earthquake.

sediments of the Mississippi embayment and is of such character and dimension that it could generate major earthquakes.

3. The zone is still quite seismically active (Figure 1). More than 2,000 earthquakes (of which 97 percent have been too small to be felt) have been detected in the zone since 1974.

These three observations--past great earthquakes, identified geological structure, and continuing activity--constitute the reasons for the high hazard potential with which the New Madrid zone is presently regarded.

EARTHQUAKE PROBABILITY

Without a doubt, the most frequently asked and least satisfactorily answered question concerning the earthquakes of the New Madrid seismic zones is: When is the next major earthquake going to happen? Seismology cannot now (nor in the near future) answer this question in a deterministic fashion (i.e., accurately predict earthquakes), but a probabilistic assessment is possible. In a recent study, Johnston and Nava (1985) estimated the probability of occurrence of large New Madrid earthquakes for two time periods--by the end of the century and within a representative lifetime (15 and 50 years, respectively) The estimates are based on magnitude: (1) a body-wave magnitude, m_b, of 6.0 (or equivalently a surface-wave magnitude, M_s, of 6.3) which could be destructive over an area of one or more counties and (2) a body-wave magnitude of 7.0 (surface-wave magnitude of 8.3) which is considered equivalent to a repeat of one of the great New Madrid events of 1811-1812. Using these magnitude categories, the determined probabilities are as follows:

Body Wave Magnitude	Probability (%)	
	1985 to 2000	1985 to 2035
m_b 6.0 (M_s 6.3)	40-63	86-97
m_b 7.0 (M_s 8.3)	0.3-1.0	2.7-4

A number of assumptions about the seismic behavior of New Madrid were necessary in order to generate the above probability ranges. The approach used and the assumptions that went into the final probability estimates are described briefly below.

Probability estimates require that the seismic zone behaves in a roughly predictable or period manner. This cannot be proven for large New Madrid events because of an incomplete data set over many seismic cycles, but smaller earthquakes exhibit a well behaved recurrence pattern. Therefore, the authors took instrumentally recorded data from the past nine years (see Figure 1) and a historical list of earthquakes of the past 158 years, determined the recurrence relationships for this data set, and then extrapolated to large magnitudes. This yielded an estimate of the average recurrence or repeat time in years between New Madrid earthquakes for a given magnitude range. For m_b 6.0, the average repeat time is 70 years. (The last such event occurred 90 years ago in 1895.) For m_b 7.0 (M_s 8.3), the average repeat time is 550 years. (The last such event was in 1812, 173 years ago.) These estimates apply to data from the entire region shown in Figure 1. If only the small region is considered (within the rectangle of Figure 1), repeat times approximately double. There are sound geophysical reasons for choosing the larger source zone.

Once the average repeat time is established, both cumulative and conditional probabilities can be determined. Cumulative probability tells us the likelihood that a quake of a certain magnitude would have occurred by now (the present) given the date of the last occurrence and the average recurrence interval. Conditional probability estimates the likelihood of occurrence during a future specified time period (i.e., 15 and 50 years--this study). Obviously, conditional probabilities are of greater interest than cumulative and are therefore emphasized in this study.

In order to make the final probability computations it is necessary to know the manner in which actual earthquake repeat times, for a given magnitude range, are dispersed about the estimated mean repeat time. This is described statistically in terms of a probability distribution with a given standard deviation. Such information for large magnitude New Madrid events is lacking; the authors' approach, therefore, was to take a number of different distributions and a range of standard deviations from the literature of studies of other active earthquake zones and apply these to New Madrid. This approach allowed for a large uncertainty in the actual (but unknown) behavior of New Madrid. This results in a range of probability values as quoted above rather than a single number.

Figures 3-5 are graphs of Gaussian conditional probabilities from m_b 6.0, m_b 6.6, and m_b 7.0 earthquakes (M_s 6.3, M_s 7.6, and M_s 8.3, respectively), graphs on which one can see the effect that the standard deviation exerts on the probability values. The types of probability distribution employed also have an effect but to a lesser degree. The date of last occurrence, the present (1985), and the mean recurrence time are indicated on the horizontal time axis. Shading illustrates the probability range as standard deviation is varied from 33 percent to 50 percent of the mean repeat time. Calculations were done for four different statistical representations--Gaussian, log-normal, Weilbull, and Poisson--but only Gaussian is shown here. Poisson statistics, which yield a constant conditional probability, are not appropriate for this analysis; therefore, only the Gaussian, log-normal, and Weibull distributions were used to obtain the probability ranges quoted above.

In conclusion, the authors estimate that there is a medium probability of a locally destructive New Madrid earthquake in the next 15 years (40 percent to 63 percent) and a high probability (86 percent to 97 percent) in the next 50 years. The probability for a great New Madrid event is less than 1 percent by the turn of the century and less than 4.0 percent during the next 50 years. These estimates are of necessity based on a number of unproven assumptions about the New Madrid zone; however, every effort was made to take an appropriate and comprehensive range of estimates in order to bracket the actual probability for future destructive earthquakes in the central United States.

PROBABILITY OF A MAGNITUDE (Ms) 8.3 EARTHQUAKE

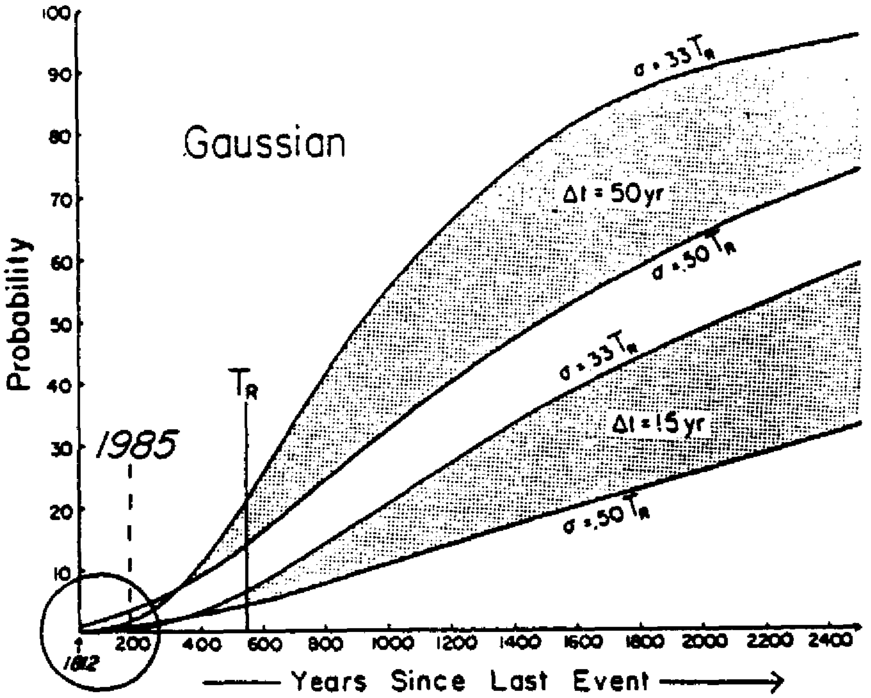

FIGURE 3(a) Gaussian conditional probability computed for magnitude m_b 7.0 (M_s 8.3) earthquake. The last such event occurred in 1812 and the mean repeat time (T_R) is 550 years. The shaded region represents the range of conditional probability as the standard deviation is varied from 33 percent to 50 percent of T_R. Future time intervals (Δt) of 15 and 50 years are depicted.

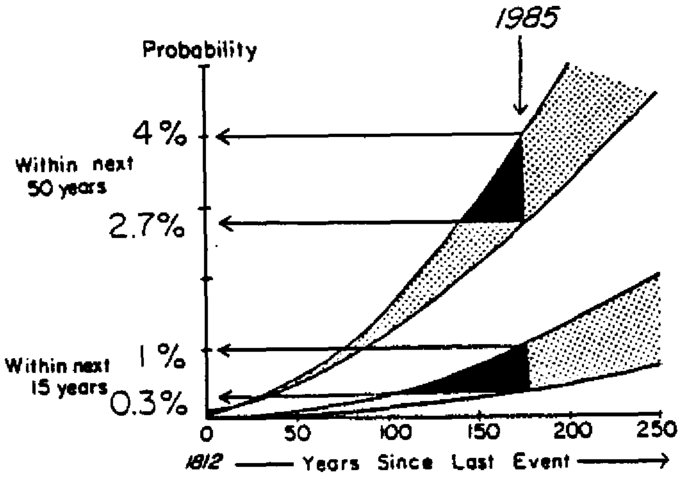

FIGURE 3(b) An expanded view of the circled region near the origin of Figure 3(a). The probability ranges are those quoted in the text.

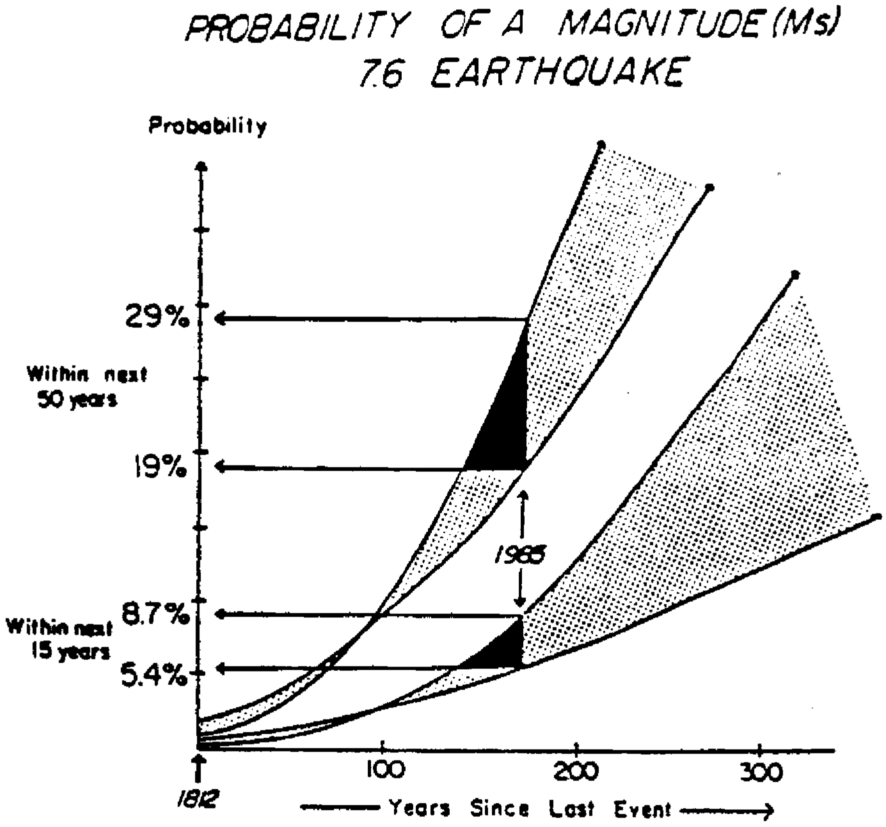

FIGURE 4 Conditional probability representation of an m_b 6.6/M_s 7.6 earthquake. Graph description follows Figure 3(a).

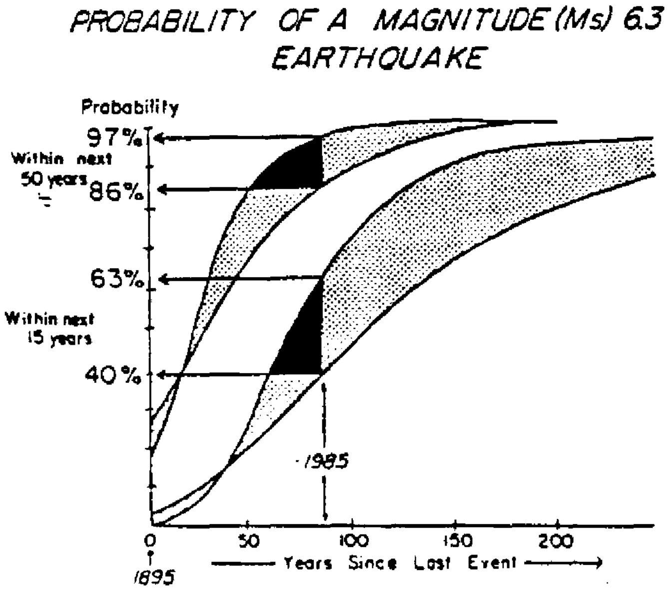

FIGURE 5 Conditional probability representation of m_b 6.0/M_s 6.3 earthquake. Graph description follows Figure 3(a).

REFERENCES

Hopper, M. G., S. T. Algermissen, E. E. Dobrovolny, 1983. Estimation of Earthquake Effects Associated with a Great Earthquake in the New Madrid Seismic Zone. USGS Open File Report 83-179. Washington, D.C. : U.S. Geological Survey.

Johnston, A. C. 1982. "A Major Earthquake Zone on the Mississippi." Scientific American 246 (4):60-68.

Johnston, A. C., and S. J. Nava. 1982. Investigations of the New Madrid Seismic Zone. Submitted to the Journal of Geophysical Research.

Mekeon, F. A. and L. C. Pakiser, Editors. 1982. Investigation of the New Madrid, Missouri, Earthquake Region. USGS Professional Paper 1236. Washington, D.C.: U.S.Geological Survey.

Nuttli, O. W. 1983. "Average Seismic Source-Parameter Relations for Mid-Plate Earthquake." Bulletin of the Seismic Society of America 73(2): 519-535.

EVALUATION OF THE EARTHQUAKE GROUND-SHAKING HAZARD FOR EARTHQUAKE-RESISTANT DESIGN

WALTER W. HAYS

This paper describes current research that can be applied to evaluate the earthquake ground-shaking hazard in any geographic region. Because most of the spectacular damage that takes place during an earthquake is caused by partial or total collapse of buildings as a result of ground shaking or the triggering of geologic effects such as ground failures and surface faulting, an accurate evaluation of the ground-shaking hazard is an important element of: (1) vulnerability studies; (2) specification of seismic design parameters for earthquake-resistant design of buildings, lifeline systems, and critical facilities; (3) assessment of risk (chance of loss); and (4) the specifications of appropriate building codes. Although the physics of ground-shaking, a term used to describe the vibration of the ground during an earthquake, is complex, ground-shaking can be explained in terms of body waves (compressional, or P, and shear, or S) and surface waves (Rayleigh and Love) (see Figure 1). Body and surface waves cause the ground and, consequently, a building and its contents and attachments to vibrate in a complex manner. Shear waves, which cause a building to vibrate from side to side, are the most damaging waves because buildings are more susceptible to horizontal vibrations than to vertical vibrations.

The objective of earthquake-resistant design is to construct a building so that it can withstand the vibrations caused by body and surface waves. In earthquake-resistant design, knowledge of the amplitude, frequency composition, and time duration of vibrations is needed. The quantities are determined empirically from strong motion accelerograms recorded in the geographic area or in other areas having similar geologic characteristics.

In addition to ground-shaking, the occurrence of earthquake-induced ground failures, surface faulting, and, for coastal locations, tsunamis also must be considered. Although ground failures induced during earthquakes have caused many thousands of casualties and millions of dollars in property damage throughout the world, the impact in the United States has been limited primarily to economic loss. During the 1969 Prince William Sound, Alaska, earthquake, ground failures caused about 60 percent of the estimated $500 million total loss; landslides, lateral spread failures, and flow failures caused damage to highways, railway grades,

---

Dr. Hays is Deputy for Research Applications, Office of Earthquakes, Volcanoes, and Engineering, U.S. Geological Survey, Reston, Virginia. He prepared this paper as background information for those making presentations at the BSSC meetings in January and February 1985.

bridges, docks, ports, warehouses, and single-family dwellings. In contrast to ground failures, deaths and injuries from surface faulting are unlikely; however, buildings and lifeline systems located in the fault zone can be severely damaged. Tsunamis, long period water waves caused by the sudden vertical movement of a large area of the sea floor during an earthquake, have produced great destruction and loss of life in Hawaii and along the West Coast of the United States. Tsunamis have occurred in the past and are a definite threat in the Caribbean. Historically, tsunamis have not been a threat on the East Coast.

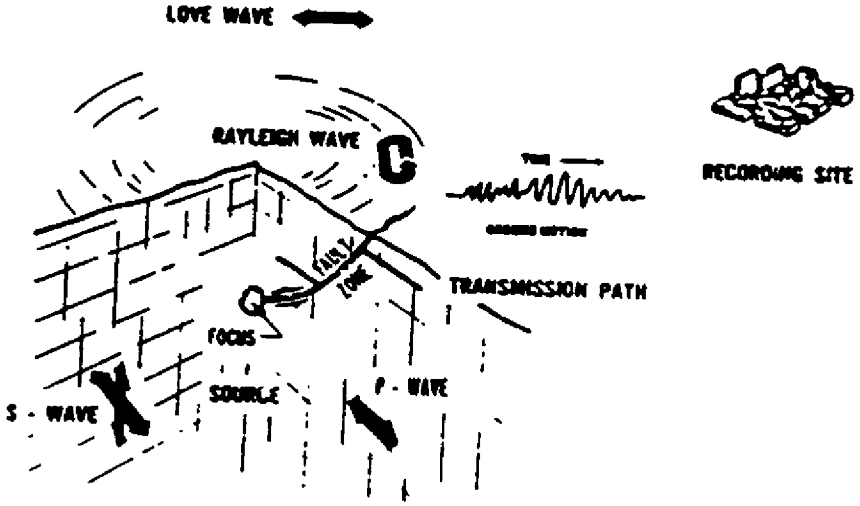

FIGURE 1 Schematic illustration of the directions of vibration caused by body and surface seismic waves generated during an earthquake. When a fault ruptures, seismic waves are propagated in all directions, causing the ground to vibrate as a consequence of the ground-shaking, and damage takes place if the building is not designed to withstand these vibrations. P and S waves mainly cause high-frequency (greater than 1 Hertz) vibrations that are more efficient in causing low buildings to vibrate. Rayleigh and Love waves mainly cause low-frequency vibrations that are more efficient than high-frequency waves in causing tall buildings to vibrate.

EVALUATION OF THE GROUND-SHAKING HAZARD

No standard methodology exists for evaluating the ground-shaking hazard in a region. The methodology that is used (whether deterministic or probabilistic) seeks answers to the following questions:

1. Where have past earthquakes occurred? Where are they occurring now?
2. Why are they occurring?
3. How big are the earthquakes?
4. How often do they occur?
5. What are the physical characteristics (amplitude,frequency composition, duration) of the ground shaking and the physical effects on buildings and other facilities?
6. What are the options for achieving earthquake-resistant design?

The ground-shaking hazard for a community (Figure 2) may be presented in a map format. Such a map displays the special variation and relative severity of a physical parameter such as peak ground acceleration. The map provides a basis for dividing a region into geographic regions or zones, each having a similar relative severity or response throughout its extent to earthquake ground-shaking. Once the potential effects of ground-shaking have been defined for all zones in a region, public policy can be devised to mitigate its effects through appropriate actions such as avoidance, land-use planning, engineering design, and distribution of losses through insurance (Hays, 1981). Each of these mitigation strategies require some sort of zoning (Figure 2). The most familiar earthquake zoning is contained in the Uniform Building Code (UBC) whose aim is to provide a minimum earthquake-resistant design standard that will enable the building to:

1. Resistant minor earthquakes without damage,
2. Resist moderate earthquakes without structural damage but with some nonstructural damage, and
3. Resist major earthquakes with structural and nonstructural damage but without collapse.

HISTORY OF SEISMIC ZONING

Zoning of the earthquake ground-shaking hazard--the division of a region into geographic areas having a similar relative severity or response to ground-shaking--has been a goal in the contiguous United States for about 50 years. During this period, two types of ground-shaking hazard maps have been constructed. The first type (Figure 3) summarizes the empirical observations of past earthquake effects and makes the assumption that, except for scaling differences, approximately the same physical effects will occur in future earthquakes. The second type (Figures 4-6) utilizes probabilistic concepts and extrapolates from regions having past earthquakes as well as from regions having potential earthquake sources, expressing the hazard in terms of either exposure time or return period.

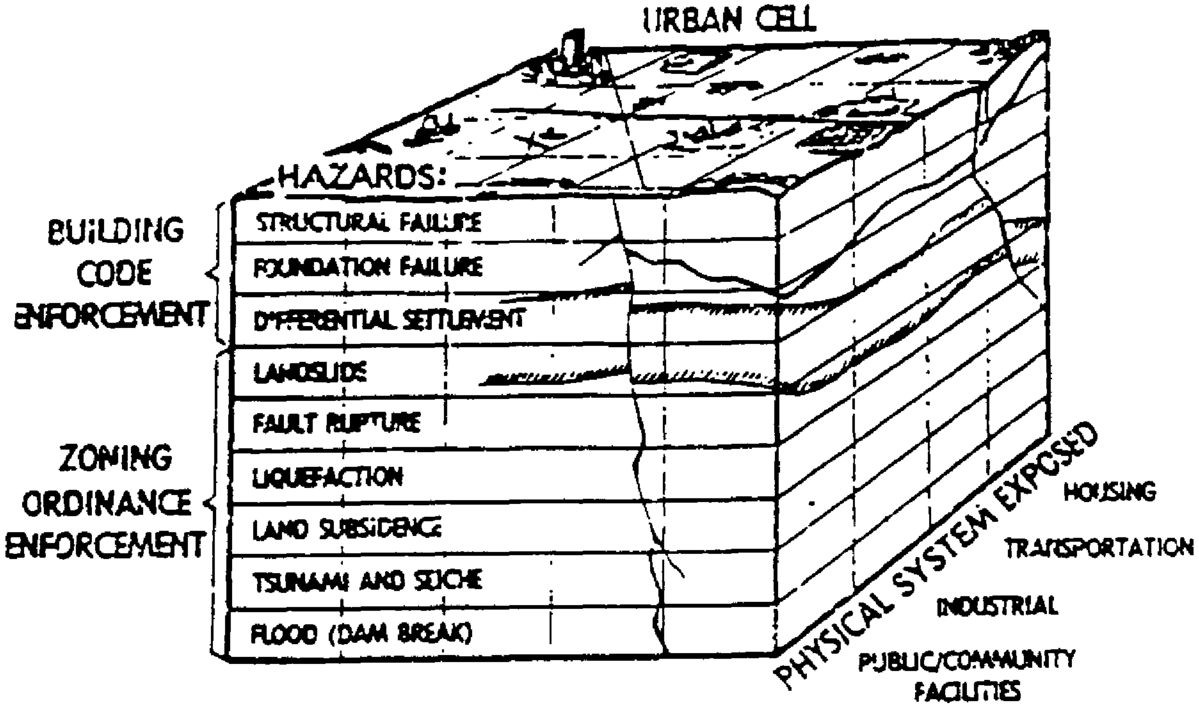

FIGURE 2 Schematic illustration of a typical community having physical systems (public/community facilities, industrial, transportation, and housing) exposed to earthquake hazards. Evaluation of the earthquake hazards provides policymakers with a sound physical basis for choosing mitigation strategies such as avoidance, land-use planning, engineering design, and distribution of losses through insurance. Earthquake zoning maps are used in the implementation of each strategy, especially for building codes.

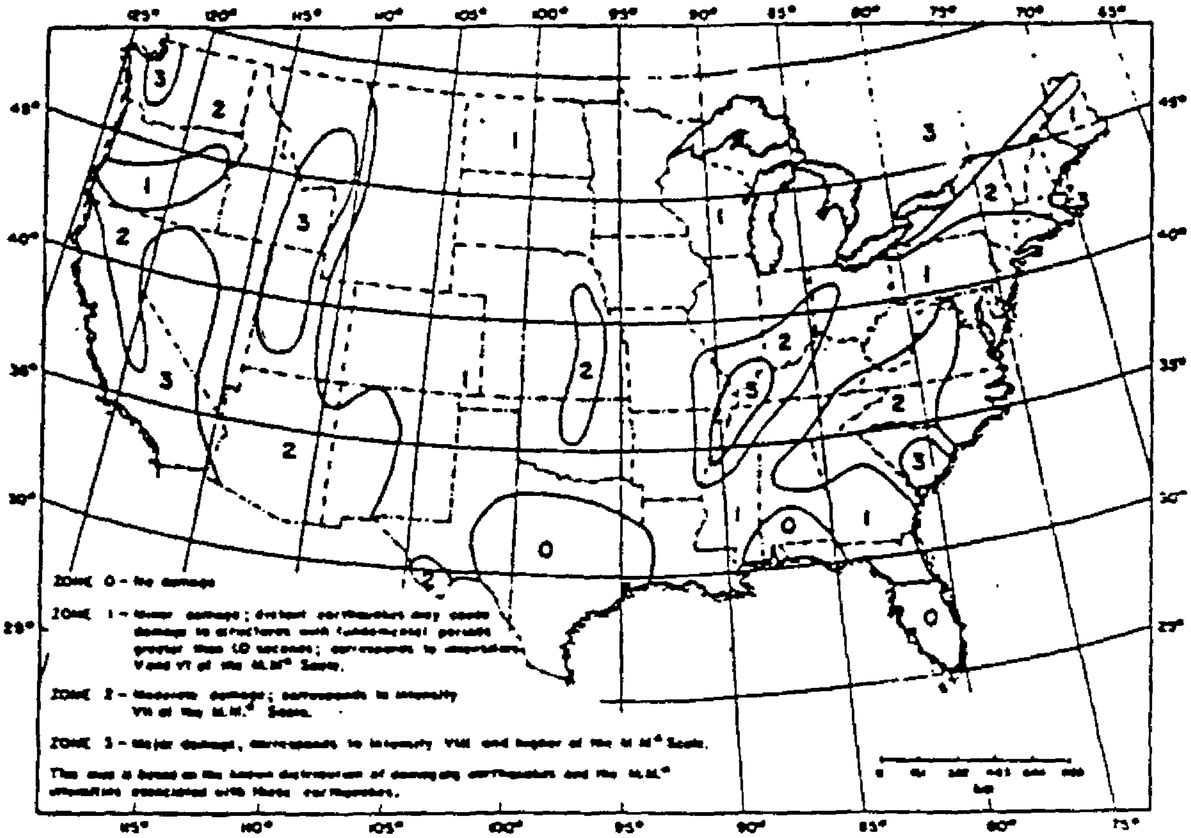

FIGURE 3 Seismic hazard zones based on historical modified Mercalli intensity (MMI) data and the distribution of damaging earthquakes (Algermissen, 1969). This map was adopted in the 1970 edition of the UBC and incorporated, with some modifications, in later editions. Zone 3 depicts the greatest hazard and corresponds to MMI VIII and greater.

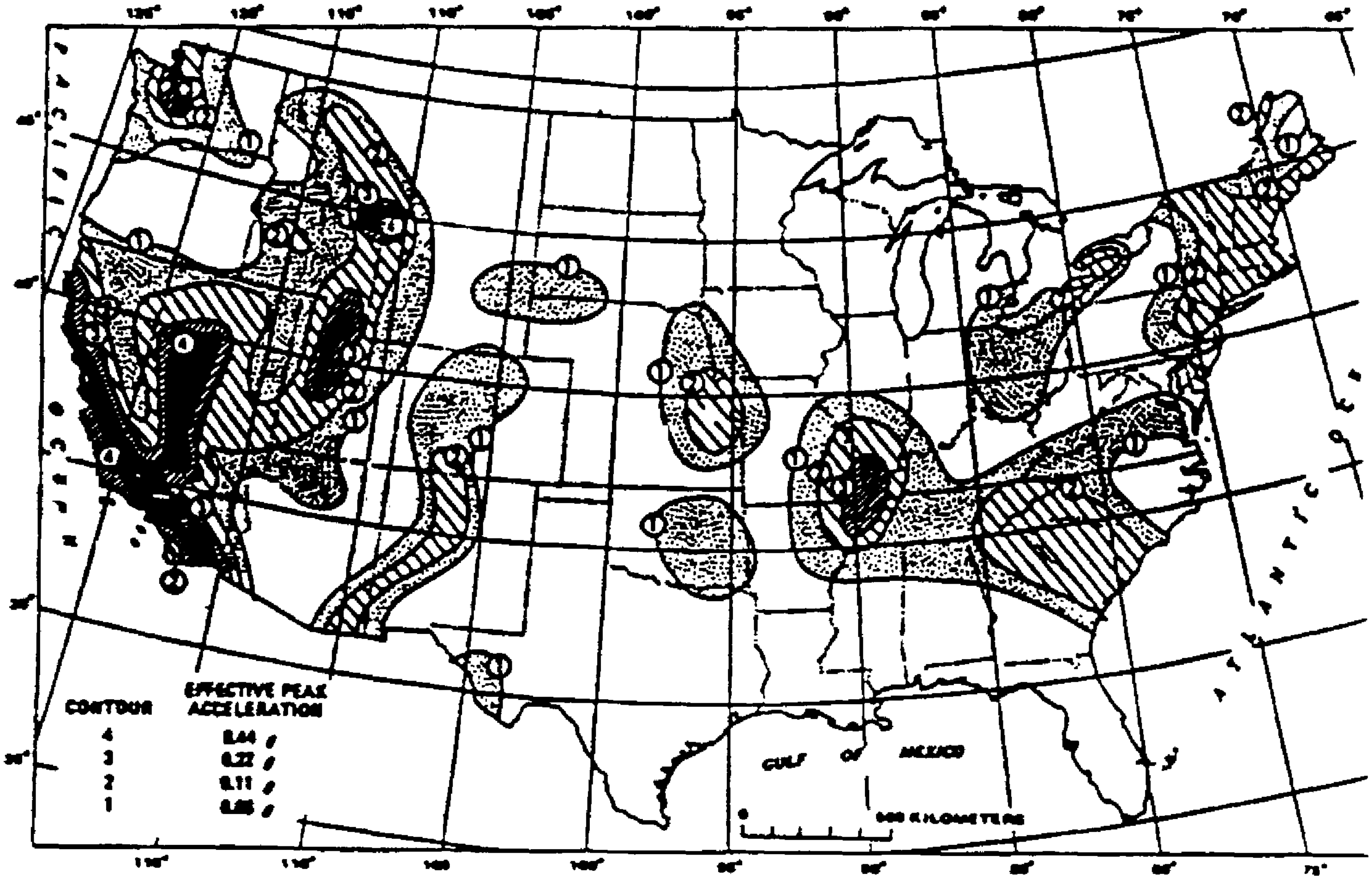

FIGURE 4 Map showing preliminary design regionalization zones for the contiguous United States proposed by the Applied Technology Council (ATC) in 1978. Contours connect areas underlain by rock having equal values of effective peak acceleration. Mapped values have a 90 percent probability of not being exceeded in a 50-year period. Zone 1 represents the lowest hazard (0.06 g). Sites located in Zone 4 require site-specific investigations. This map was based on research by Algermissen and Perkins (1976).

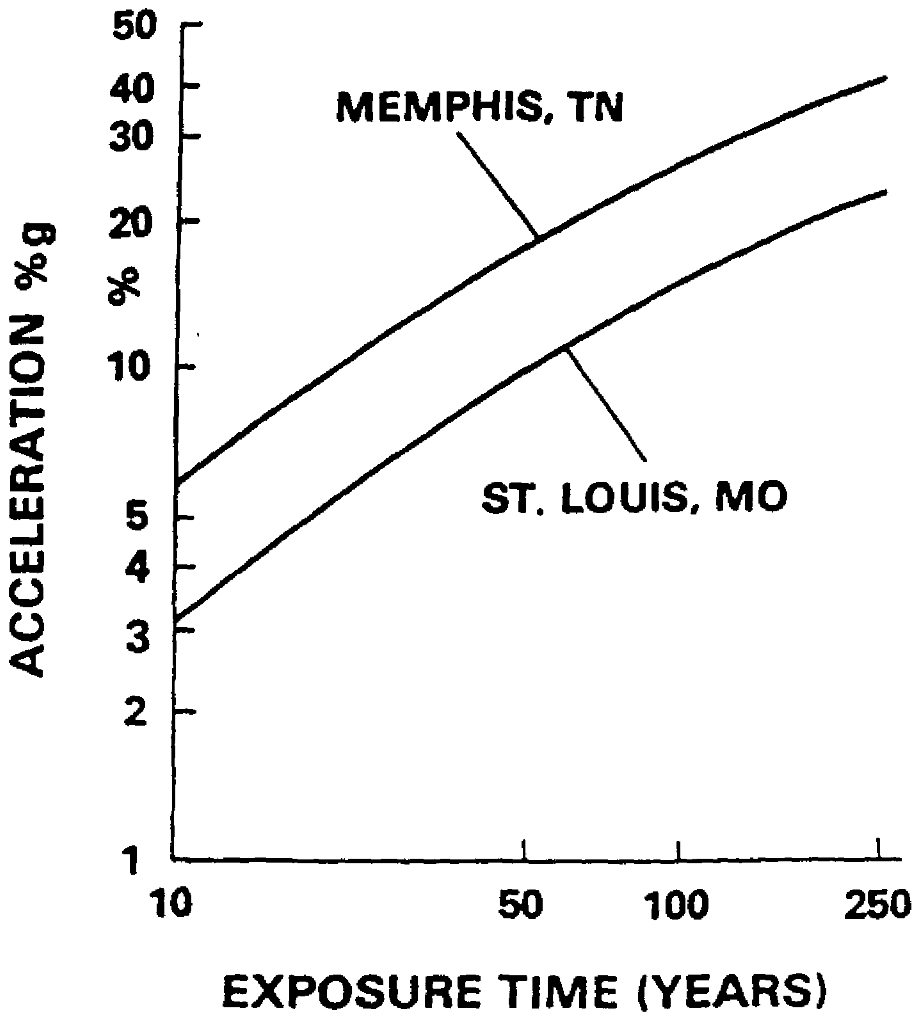

FIGURE 5 Graph showing levels of peak horizontal ground acceleration expected at bedrock sites in the Memphis, Tennessee, and the St. Louis, Missouri, areas in various exposure times. The values of peak acceleration have a 90 percent probability of nonexceedance. An exposure time of 50 years corresponds to the useful life of an ordinary building and is typically used in many building codes.

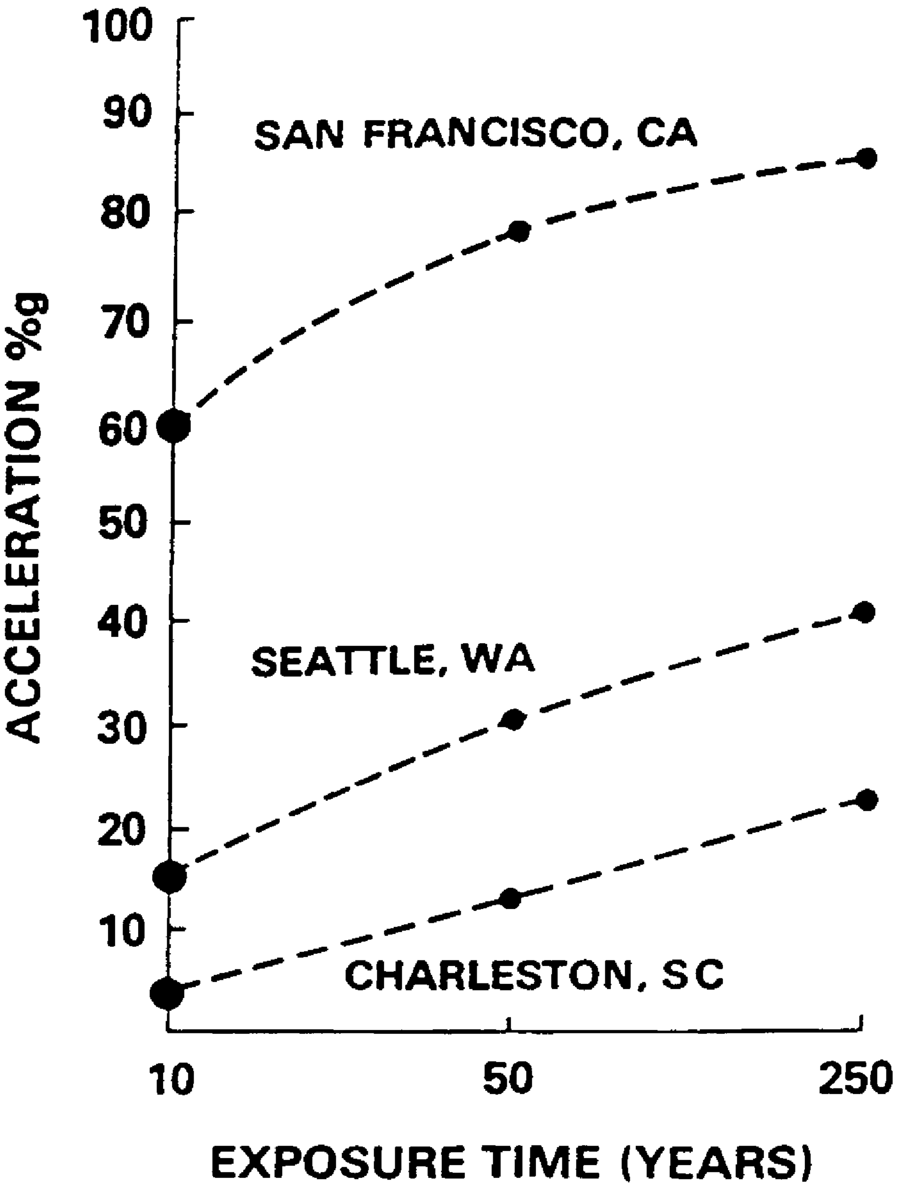

FIGURE 6 Graph showing levels of peak horizontal ground acceleration expected at bedrock sites in the Charleston, South Carolina, and the Seattle, Washington, areas in various exposure times. For comparison, San Francisco, California, also is included. The values of peak acceleration have a 90 percent probability of nonexceedance. An exposure time of 50 years corresponds to the useful life of an ordinary building and is typically used in many building codes.

PROCEDURE FOR EVALUATING THE GROUND-SHAKING HAZARD

Construction of a ground-shaking hazard map requires data on:

1. Seismicity,
2. Earthquake source zones,
3. Attenuation of peak acceleration, and
4. Local ground response.

The procedure for constructing a ground-shaking hazard map is illustrated schematically in Figure 7. Except for probabilistic considerations a deterministic map would follow the same general procedure.

RESEARCH PROBLEMS

A number of complicated research problems are involved in the evaluation of the ground-shaking hazard (Hays, 1980). These problems must be addressed if more accurate specifications of the ground-shaking hazard are desired. The problems can be categorized in four general areas--seismicity, nature of the earthquake source zone, seismic wave attenuation, and local ground response--with each area having a wide range of technical issues. Presented below are representative questions, which generally cannot be answered with a simple "yes" or "no," that illustrate the controversy associated with ground-shaking hazard maps.

Seismicity

- Can catalogs of instrumentally recorded and felt earthquakes (usually representing a regional scale and a short time interval) be used to give a precise specification of the frequency of occurrence of major earthquakes on a local scale?
- Can the seismic cycle of individual fault systems be determined accurately and, if so, can the exact position in the cycle be identified?
- 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 recurrence of this event be specified? Can the frequency of occurrence of small earthquakes be specified?
- Can seismic gaps (i.e., locations having a noticeable lack of earthquake activity surrounded by locations having activity) be identified and their earthquake potential evaluated accurately?
- Does the geologic evidence for the occurrence of major tectonic episodes in the geologic past and the evidence provided by current and historic patterns of seismicity in a geographic region agree? If not, can these two sets of data be reconciled?

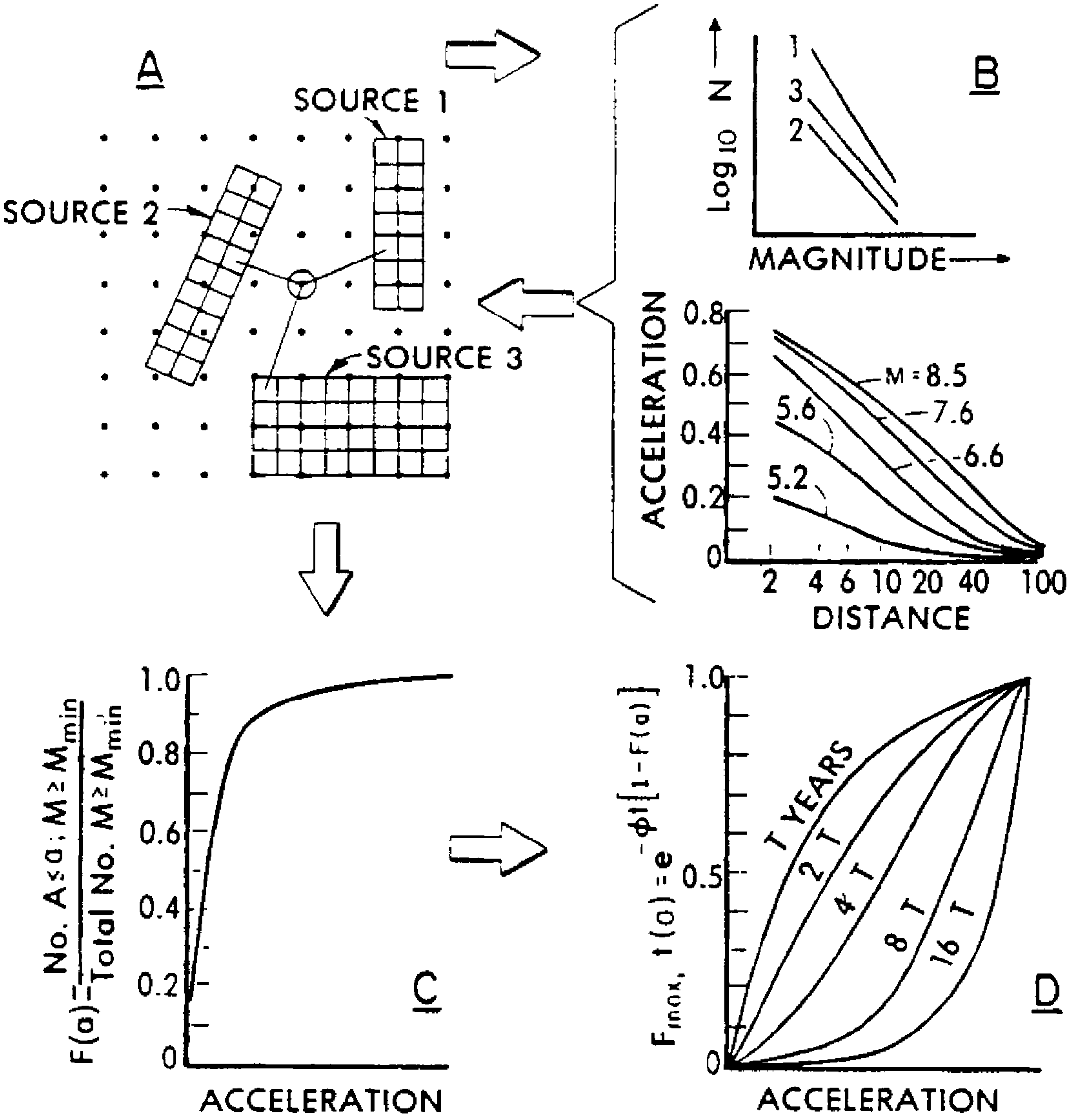

FIGURE 7 Procedure for constructing a grounding-shaking hazard map.

The Nature of the Earthquake Source Zone

- Can seismic source zones be defined accurately on the basis of historic seismicity, on the basis of geology and tectonics, or on the basis of historical seismicity generalized by geologic and tectonic data? Which approach is most accurate for use in deterministic studies? Which approach is most accurate for use in probabilistic studies?

- Can the magnitude of the largest earthquake expected to occur in a given period of time on a particular fault system or in a seismic source zone be estimated correctly?

- Has the region experienced its maximum or upper-bound earthquake?

- Should the physical effects of important earthquake source parameters such as stress drop and seismic moment be quantified and incorporated in earthquake-resistant design even though they are not traditionally used?

Seismic Wave Attenuation

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

- Do peak ground-motion parameters (e.g., peak acceleration) saturate at large magnitudes?

- Are the data bases adequate for defining bedrock attenuation laws? Are they adequate for defining soil attenuation laws?

Local Ground Response

- For specific soil types is there a discrete range of peak ground-motion values and levels of dynamic shear strain for which the ground response is repeatable and essentially linear? Under what in-situ conditions do non-linear effects dominate?

- Can the two- and three-dimensional variations of selected physical properties (e.g., thickness, lithology, geometry, water content, shear-wave velocity, and density) be modelled accurately? Under what physical conditions do one or more of these physical properties control the spatial variations, the duration, and the amplitude and frequency composition of ground response in a geographic region?

- Does the uncertainty associated with the response of a soil and rock column vary with magnitude?

CONCLUSIONS

Improved maps of the earthquake ground-shaking hazard will come as relevant geologic and seismological data are collected and synthesized. The key to progress will be the resolution of the research problems identified above.

REFERENCES

Algermissen, S. T. 1969. "Seismic Risk Studies in the United States." In Proceedings of the 4th Conference on Earthquake Engineering, Vol. 1.

Algermissen, S. T., and D. M. Perkins. 1976. A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States. USGS Open File Report 76-416. Reston, Virginia: U.S. Geological Survey.

Applied Technology Council. 1978. Tentative Provisions for the Development of Seismic Regulations for Buildings. Report ATC 3-06. Palo Alto, California: Applied Technology Council.

Hays, W. W. 1980. Procedures for Estimating Earthquake Ground Motions. USGS Professional Paper 1114. Reston, Virginia: U.S. Geological Survey.

Hays, W. W. 1981. Facing Geologic and Hydrologic Hazards-Earth Science Considerations. USGS Professional Paper 1240. Washington, D.C.: U.S. Government Printing Office.