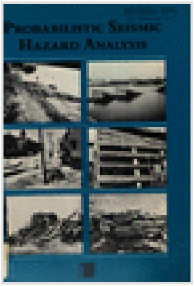

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Nügato, Japan
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April 18, 1906

Mexico City, Mexico
September 19, 1985

Charleston, South Carolina
August 31, 1886

Tsunami Damage
Seward, Alaska
March 27, 1964

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PROBABILISTIC SEISMIC HAZARD ANALYSIS

Panel on Seismic Hazard Analysis
Committee on Seismology
Board on Earth Sciences
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

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COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND RESOURCES

PREFACE

The Committee on Seismology established the Panel on Seismic Hazard Analysis to assess methodologies according to the charter given in Appendix A. The panel concentrated on the probabilistic method but also examined alternatives.

The panel's discussions included a review of the extensive hazard analyses for the eastern United States by the Electric Power Research Institute (EPRI) and Lawrence Livermore National Laboratory (LLNL). A questionnaire about the attributes of seismic hazard analysis methods was sent to members of the scientific and technical community and decision makers. The questions and a summary of responses to them are presented in Appendix B.

The report is addressed to decision makers with a modest scientific and technical background and to the scientific and technical community.

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EXECUTIVE SUMMARY

The purpose of Probabilistic Seismic Hazard Analysis (PSHA) is to evaluate the hazard of seismic ground motion at a site by considering all possible earthquakes in the area, estimating the associated shaking at the site, and calculating the probabilities of these occurrences. The Panel on Seismic Hazard Analysis is charged with assessment of the capabilities, limitations, and future trends of PSHA in the context of alternatives. The report identifies and discusses key issues of PSHA and is addressed to decision makers with a modest scientific and technical background and to the scientific and technical community.

The Panel recognizes the decision makers' needs for a concise quantitative estimate of seismic hazards to structures whose designs they must approve and to people and properties they are responsible for protecting. A PSHA is intended to meet these needs by presenting probabilities of earthquake ground shaking and associated uncertainties, which are obtained by integrating all available data as well as expert opinions. Given the current limited knowledge and understanding of the earthquake process, even despite recent advances, all assessments of earthquake hazard are inherently uncertain. The communication of an assessment of the hazard--and its attendant uncertainties--among earth scientists, engineers, and users of the assessment has proven to be a difficult task. PSHA has evolved over the last decade to the point where it is, for many users, the method of choice. Previous concerns about its use, such as those noted in the 1980 NRC panel report _Earthquake Research for the Safer Siting of Critical Facilities_, have been largely overcome. The principal conclusion here is that PSHA, when carried out with an appropriate level of sophistication to satisfy the needs of the user, can be regarded as an acceptable procedure for describing the seismic hazard. It is recognized that decision makers or policy makers who do not use probability methods on a regular basis may have difficulty initially in evaluating the results of a PSHA or its implications.

In the body of this report, attention is focused primarily on PSHA. In chapter 2, the panel explains PSHA and describes the alternative earthquake hazard analysis techniques that are available--from fully deterministic procedures, through hybrid (partly deterministic and partly probabilistic), to fully probabilistic procedures. Chapter 3 discusses six major PSHA issues: (1) needs of the users, (2) how PSHA captures earth science information, (3) uncertainty and instability, (4) testing PSHA and liability, (5) aggregation of input parameters, and (6) how PSHA should be used by decision makers. A description of what constitutes an adequate PSHA appears in chapter 4 based on the findings of the panel. Areas for the immediate application of PSHA are recommended in chapter 5, and likely future directions in PSHA are discussed in chapter 6.

The panel was chosen to represent the communities of seismic hazard analysis, earth sciences, and earthquake engineering. Input to our deliberations came from a wide cross section of these fields, through presentations to the panel and responses to a questionnaire (summarized in Appendix B).

DETERMINISTIC VERSUS PROBABILISTIC SEISMIC HAZARD ANALYSIS

The traditional approach in seismic hazard analysis in this country has been deterministic: a single, "maximum" earthquake is specified by magnitude and location with respect to a site of interest, and the associated ground motion is assessed and used to design or evaluate the safety of a facility. The deterministic approach may be justified, for example, for major earthquakes on a given segment of a plate boundary fault that is known to break repeatedly, generating similar size earthquakes characteristic to the fault segment. The probabilistic approach may be used to account for the likelihood that a range of small and large earthquakes may occur along a given fault and that various faults in a broader region might affect the site.

As described in chapter 2, Deterministic Seismic Hazard Analysis (DSHA: Type 1) selects one or more earthquakes as the target for designing an earthquake resistant structure. The target earthquake for a critical structure (usually the "maximum earthquake" or "maximum credible earthquake") is usually selected by considerations of the historical seismicity record and physical characteristics of the seismic sources. Various characteristics of the target earthquake are then described in specific terms (e.g., magnitude and peak ground motions). DSHA does not consider the likelihood of the occurrence of the target earthquake, nor does it offer any insight into the importance of the target earthquake relative to other possible seismic hazards, such as those due to smaller but closer earthquakes or larger but more distant earthquakes.

PSHA is a probabilistic analysis of the earthquake hazard that addresses the questions of <u>how strongly</u> and <u>how often</u> the ground will shake, by considering all possible earthquakes that might affect the site. The range of ground motions at a site resulting from earthquakes that might occur on a variety of seismic sources is estimated by using an attenuation function to translate to the site through distance the ground motions associated with earthquakes that are considered. The rate of earthquake occurrence on each seismic source is also considered. Thus, PSHA combines information on earthquake size, location, probability of occurrence, and resulting ground motion to give results in terms of ground motion and associated annual probability of occurrence (or exceedance). An important issue for PSHA is which ground motion measures will meet the needs of various users (e.g. peak acceleration, response spectra, etc.).

When seismic hazard must be quantified in the face of uncertainty in the locations of seismic sources, magnitude distributions, and ground-motion estimates, PSHA can incorporate and display the range of scientific opinion regarding these issues. One way to do this is to identify various hypotheses and models to describe each earth science phenomena involved. When this is done, the range of uncertainty in the PSHA corresponding to the range of hypotheses can and should be explicitly displayed, so that the decision maker will be aware of the uncertainties and will not have a false impression of accuracy that might be associated with a single valued hazard estimate. Expert judgment can be employed to assign subjective probabilities to each hypothesis and thus identify to the decision makers where, in the range of uncertainty, the prevailing weight of opinion would assign the risk.

When the uncertainty in the PSHA results is too large to be useful for decision making, a consensus could still be sought among experts who may capture by an indepth DSHA analysis, subtle but crucial details of earth science information which escaped the quantification procedure in PSHA.

The panel's findings and recommendations have been made with regard to the three major issues of PSHA, namely, (1) meeting of the needs of users, (2) capturing the earth science information, and (3) uncertainty and variability.

MEETING THE NEEDS OF USERS

Panel Findings

The panel identified four classes of PSHA users according to the seismic safety level and lifetime of the facility of concern:

- Designers, code writers, regulators, and owners for conventional facilities are interested primarily in seismic hazard estimation for the annual probability of exceedance in the range of 10^{-2} to 10^{-3} (i.e., the ground motion that is exceeded with annual probability of 0.01 to 0.001). These users usually do not require explicit display of uncertainty. However, agreement on the implicit treatment of uncertainty in the hazard estimates among practitioners is desirable for a stable and logical basis for decision.
- Owners and regulators of critical facilities, such as nuclear power plants, dams, and liquefied natural gas (LNG) facilities, which typically have a lifetime of 30 to 50 years. These PSHA users would like to have reliable seismic hazard estimates in the annual exceedance

probability range of 10^{-3} to 10^{-4}. A useful hazard analysis for individual critical facilities may require estimation at levels that extend down to the 10^{-6} annual exceedance probability. Higher annual levels of hazard may be tolerable during construction or for facilities with very short exposure times.

- Owners and regulators of long-term hazardous waste repositories desire hazard estimations at 10^{-2} to 10^{-4} for facility lifetimes of 10,000 years, i.e., the annual exceedance probabilities range from 10^{-6} to 10^{-8}. Hazard estimates for these lifetimes, based only on the short historical record, are highly uncertain and probably not appropriate. Such long exposure times may require qualitatively different assumptions about the earthquake processes than those at comparable annual probability levels for short lifetimes (e.g., 50 years). Paleoseismic data and other techniques under development can provide a credible basis for hazard evaluation at some sites and promise wide applicability in the future.
- A variety of other users, including federal, state, and local officials, the general public, the news media, and disaster response organizations, have important special needs for seismic hazard evaluation. Increasingly, these users are in a position to respond to information about seismic hazards given in a probabilistic format.

Given the users of PSHA, the panel evaluated the immediate potential applications of PSHA and arrived at the following recommendations.

Recommendations

1. *Simple PSHA approaches that do not involve detailed source characterization or uncertainty treatment are appropriate where the probability levels of interest are moderate (i.e., greater than 10^{-3} per year), such as for commercial buildings; where the analysis is being conducted for a noncritical facility and economic incentives justify evaluating the adequacy of conventional design based on existing building codes; or where a regional PSHA study intended for planning purposes is being conducted.*

2. *Sophisticated PSHA studies that fully characterize seismic sources and incorporate uncertainties are appropriate where the probability levels of interest are low (i.e., 10^{-3} to 10^{-6} per year or lower) such as for critical facilities; where economic and safety incentives require consideration of "rare" seismic events; or where the hazard analysis is being conducted for site-specific or subregional (multiple sites within a relatively small region) purposes that require full characterization of a unique seismic environment.*

3. *In many instances, the design of existing engineering facilities has been carried out on the basis of deterministic characterization of the hazard levels. This is true for most dams and nuclear power plants in the United States. Where reevaluation of these facilities is desired, PSHA can be particularly effective for investigating the relative levels of conservatism already present in the design bases for these facilities (e.g., what is the probability of ground motions exceeding the design basis?). The PSHA can also be used in this way to incorporate improvements in the knowledge of the tectonic environment that have accrued since the facility was built and then to display effectively the uncertainties that are present in the hazard analysis.*

Detailed aspects of a PSHA will depend on its intended application. However, the panel has found that the characteristics required of all PSHAs include the following:

a. Consistency with current understanding of the physical processes of earthquake generation and seismic energy progagation, and the current state-of-the-practice in statistical data analysis;

b. Documentation of the bases for the choice of specific models, parameters, and procedures used in the analysis; and

c. Quantification of uncertainty of the results. This may be accomplished through calculation of the probability distribution of hazard or through sensitivity analysis.

CAPTURING EARTH SCIENCE INFORMATION

Panel Findings

PSHA intends to capture as much earth science information as possible about the spatial, temporal, and size distribution of earthquakes as well as the source, path, and local site effects of strong ground motion and to transmit the annual probability that the resulting ground motion will exceed a given value at a site (hazard curve such as shown in Figure 2.5). The compact summary nature of the hazard curve provides a convenient and useful means of representing the seismic hazard under consideration, provides important information for engineering design, and makes possible a comparison of the seismic hazard with other types of hazard. However, any single PSHA hazard curve is not easily related to the input data. Because the "aggregated" results of PSHA are not always easily related to the inputs, PSHA may also obscure the unknowns and uncertainties of earth sciences data and may lead to an unwarranted sense of accuracy in the values generated. The multiple-model PSHA is designed to avoid these shortcomings by exhibiting the range of uncertainty in seismic hazard corresponding to the range of alternative hypotheses.

PSHA separates the seismic hazard problem into components, brings available data and theory to bear on each component, and then combines the information in a final analysis. Thus PSHA can take advantage of any advances made in strong ground-motion prediction. It cannot, however, incorporate multidimensional descriptions of ground shaking, such as those represented by the whole time series of observed or synthetic seismograms. These can be incorporated more easily by hybrid procedures (Type V, see chapter 4) or by deterministic or semiprobabilistic procedures (Type I, see chapter 2).

Recommendations

1. *The output of PSHA is only as good as its input. To improve the value and credibility of PSHA, one must improve the quality and increase the quantity of earth science information related to seismic hazards. Effective use of this information in earthquake hazard mitigation will also require more productive interaction among earth scientists and hazard analysts.*
2. *All PSHA should include analyses and discussions of important factors that affect or contribute to a hazard at a site or in a region. This can be done by verbal or graphical descriptions and by studies of sensitivity of the various parameters affecting a hazard estimate. These studies should give the user a better understanding of which earth science data and geologic processes most influence the seismic hazard.*
3. *Current uncertainties in seismic hazard estimation in the United States are large. Improvement of the basic data base and enhancement of our understanding of the earthquake process, as well as methods for incorporating this knowledge into PSHA, are of utmost importance if our statements of seismic hazard are to gain accuracy and thus lead to more efficient use of resources for seismic safety.*

   Major areas where attention is needed include the following:

   a. Geologic and tectonic understanding of the mechanisms, locations, and rates of crustal faulting and other deformation and their relationships to earthquake processes;

   b. Continued operation of seismic networks and physical and statistical analyses of earthquake sequences to examine aspects such as spatial and temporal nonhomogeneity, variability of earthquake occurrence rates, and validity of alternative seismicity models; and

   c. Better understanding of the characteristics of strong ground motions, including dynamic processes during earthquake rupture, seismic wave generation and propagation, and the effects of surficial geologic materials.

4. *The large uncertainties in seismic hazard analysis require further improvements in techniques for quantifying and documenting subjective probabilities, including assessment and aggregation of expert opinion. Methods must be developed to represent the resulting uncertainties in seismic hazard estimation in convenient*

ways for users of PSHA. Improved techniques and broader use of hybrid procedures using combined deterministic and probabilistic approaches are also necessary for taking full advantage of increasing data bases and of the strong points of both approaches.

UNCERTAINTY AND VARIABILITY

Panel Findings

Distinct but related problems in any seismic hazard assessment are the uncertainty of the estimate and its variability from study to study. The panel reached the following conclusions regarding these problems.

- Knowledge of earthquake processes and effects in much of the United States is meager, resulting in considerable uncertainty in seismic hazard estimates. No single measure of seismic hazard (e.g., a mean or median) is adequate to represent this basic lack of understanding; therefore, measures of uncertainty must be transmitted as part of a PSHA.
- A second problem, especially in the context of regulation, is the variability of hazard estimates. The need for stable regulatory decisions is, unfortunately, in contrast with the evolutionary nature of earth science and seismic hazard estimation technology. It is likely that, as the field matures, consensus of professional opinion and stability will increase. In the meantime, the problem can be alleviated by prescription of methods and by broader participation of experts.

Recommendation

For PSHA to be useful in the decision-making process, new applications of available decision analysis techniques are required, so that the consequences of earthquake hazard can be considered. In this regard, PSHA is completely consistent with quantitative risk analysis and decision analysis as they are applied in science, technology, and public policy. Decision makers should explicitly address the uncertainties inherent in any PSHA and should consider the costs and consequences (i.e., risks) associated with a seismic hazard. Depending on the application, the level of sophistication of these risk analyses may vary from subjective evaluations to comprehensive decision analyses. Making critical decisions with important social and economic consequences will be helped by additional developments in applying decision analysis to PSHA results, and the panel encourages such developments.

2

WHAT IS PROBABILISTIC SEISMIC HAZARD ANALYSIS (PSHA)?

INTRODUCTION

Virtually every important decision regarding the evaluation of earthquake effects on people and manmade facilities is made using some form of probabilistic seismic hazard or seismic risk analysis. Sometimes these analyses are conducted informally, with probabilities or likelihoods assessed intuitively with subjective expert opinion. In such instances our judgment, intuition, and experience are adequate to assess relative probabilities of occurrence and to make rational decisions on the optimum course of action (or inaction) to take. Sometimes the judgments made are so natural and intuitive that they are made largely unconsciously; our experience and confidence allows assurance that the results are nearly optimal.

In instances involving complicated assessments of effects derived from various geoscience and engineering disciplines, decision makers often prefer formal assessments of probabilities of earthquake occurrences and associated natural effects that may produce damage to facilities and injury or life-loss to people. Such formal assessments are usually most appropriate for recommendations on (1) regional or national seismic design requirements; (2) earthquake evaluation of important facilities whose loss would imply substantial financial hardship to owners; (3) estimation of earthquake damage and losses for emergency preparedness purposes; and (4) decision making regarding seismic safety of critical facilities (whose damage might lead to substantial life loss, injury, monetary and property loss, or threat to national security).

This report examines a formal probabilistic seismic hazard analysis (PSHA), evaluates its strengths and weaknesses, and suggests those elements of a PSHA that are considered necessary for a reasonable statement of seismic hazard. The panel does not mean to imply that subjective, informal assessments are not justified or even preferable in certain instances; indeed, they are. However, when the probabilities calculated cannot be correlated directly with observed statistics, or the consequences of earthquake damage are significant, or the uncertainties in physical interpretation for one or more scientific fields are large, formal procedures for PSHA are generally preferred. A PSHA evaluates the hazard of seismic ground motion at a site by considering all possible earthquakes in the area, estimating the associated shaking at the site, and calculating the probabilities of these occurrences. While this report focuses on the hazard of ground shaking, similar probabilistic techniques can be applied to the assessment of hazard from fault movement, liquefaction, and landslides. PSHA procedures have several advantages over less formal, more subjective evaluations:

1. Formal seismic hazard evaluation necessitates the listing and documentation of all assumptions that are important for decisions on the mitigation of seismic hazard, including the frequency of occurrence of earthquakes. The assumptions are thereby available for review and critique by others.
2. Formal analysis allows the use and integration of expert opinion from many different scientific fields and requires that these opinions be given their proper mathematical perspective as they affect the seismic hazard. Strong personalities are less likely to dominate decisions unless the input they provide is, in fact, crucial to the results being calculated.
3. The statement of seismic hazard and its uncertainty (as discussed below) can be used as input to procedures for decision making using criteria such as total cost, or cost per life saved, compared to other reducible risks.
4. Explicit evaluation of uncertainties in seismic hazard leads to conclusions regarding the relative importance of the various inputs to the analysis, thus identifying areas that require more precise specification in later studies or more research work to resolve differences of opinion and interpretation by experts. By contrast, other input, while perhaps subject to large uncertainties, might have less importance to the seismic hazard results and would thereby warrant less attention for later seismic hazard studies.
5. Properly conducted uncertainty analyses on seismic hazard can be interpreted as statements of how estimates of seismic hazard might change in the future as new data and theories become available. Thus a certain site might, in the preferred interpretation of experts and in the preferred analysis performed today, have a low seismic hazard, but there could be a finite probability that given certain data collected in the next five years, the assessment would be revised to indicate a high hazard. All of this can be formalized for use by decision makers assessing the seismic vulnerability of facilities at the site.

It is important to understand that PSHA evaluates seismic hazards, which are natural phenomena (such as shaking or fault movement) that, by themselves, do not include losses or effects on the human condition. Seismic <u>risk</u> analysis evaluates the probability of various consequences of earthquakes on the population and facilities. Only by considering these consequences through analyses, ranging from explicit decision analyses to intuitive judgments, can proper decisions be made (in the broad sense of conserving and optimizing the use of human and natural resources). Earthquake fault movement and the strong ground motion associated with earthquakes do not by themselves cause loss of life or property. It is the responses of natural and manmade structures and the impact of these responses on the human environment that cause loss. Thus, PSHA will prove to be a useful tool for accurate decision making only insofar as it addresses aspects of earthquake effects that can ultimately be used to estimate damage and loss. An important consequence is that the analyst conducting a PSHA must always be aware of the uses to which his results will be put and must design his results to be applicable to those uses.

A PSHA has the ability to, and should, incorporate all knowledge about the earthquake phenomenon relevant to the description of the hazard. This includes known or suspected behavior of earthquakes in a "nonrandom" way in time, space, and size, hypothesized or proven models that describe the propagation of seismic waves in the earth's crust, and empirical or theoretical means of estimating or determining the effects of near-surface rocks or soils on seismic waves. Predictions of earthquake occurrences are not an alternative means of evaluating seismic hazards, but are a more precise model of earthquake occurrences in time, space, and size than current alternatives. These more precise models can and should be incorporated into PSHA when they are available. In fact, PSHA provides the best format for incorporating earthquake predictions into the decision-making process as it allows the uncertainty of the prediction to be taken into account, and it allows a comparison of perceived hazard on the same basis with and without the prediction.

In recent years, the state of the art in the earth sciences has advanced, and the treatment of uncertainty has significantly expanded such that PSHA can display the different types of uncertainty at any step in the process. This systematic treatment has exposed the high levels of uncertainty inherent in the hazard estimates. Thus, despite advances in our understanding of earthquake processes, the net effect during the past few years has been an apparent increase in the uncertainty associated with numerical probabilistic seismic hazard estimates. This increase should not be viewed as a weakness in probabilistic seismic hazard estimation but rather as a fuller disclosure of problems associated with hazard estimation, deterministic or probabilistic.

CALCULATIONS

The objective of seismic hazard analysis is to provide a formal estimate of the earthquake threat at a specific site. Typically, the threat is expressed in terms of the amplitude of seismic shaking (a peak acceleration or velocity of the shaking, an amplitude of the response spectrum of ground motion, or the duration of strong shaking--see the glossary for definitions). For special cases, hazard might be caused by the displacement on the causative fault, or by failure of soil deposits (liquefaction slumps or landslides). The time horizon for these PSHA calculations is typically 30 to 50 years, the economic lifetime of engineered structures and facilities. Application to nuclear waste disposal problems implies much longer time periods, and the uncertainties inherent in such calculations require special consideration. The hazard estimate is a function of available information relevant to earthquake activity in the region.

The panel presents here a very brief introduction to PSHA. More detailed developments are contained elsewhere (e.g., EPRI, 1982, and references contained therein). A typical PSHA seeks to estimate the annual probabilities of exceedance as a function of a single amplitude of strong ground shaking, e.g., the peak acceleration of the ground-motion as shown in Figure 2.1. A more general formulation of seismic hazard analysis, that includes a vectorial representation of ground-motion characteristics, of which Figure 2.1 is a special case, is presented in Appendix C. Figure 2.1 illustrates the four elements that are considered to calculate PSHA.

A. Seismic sources (zones or faults within which future earthquakes will occur) are delineated. From this a distribution of possible epicentral distances $f_R(r)$ is derived.

B. A rate of earthquake occurrence ν_i and a magnitude distribution $f_M(m)$ are derived for each source.

C. A ground-motion model is derived that, for any specified magnitude m and distance d, allows calculation of the probability $G_{a|m,r}(a^*)$ that a ground-motion amplitude a^* is exceeded.

D. A calculation is made of the rate ν_{a*} with which amplitude a^* is exceeded, using inputs A through C, by integrating overall possible magnitudes and distances and by accounting for their relative probabilities.

The third input is an "attenuation function" that allows estimation of the distribution of ground-motion amplitudes as a function of magnitude and distance (Figure 2.1C). The probability analysis (Figure 2.1D) integrates overall earthquake sizes and distances, and sums over all sources, to estimate the expected number of exceedances of amplitude $\underline{a}^*$ per unit time, which is an accurate estimate of the annual probability of exceedance of amplitude $\underline{a}^*$ for a low value of probability (see Appendix C).

Use of the expected number of events $\nu_{\underline{a}*}$ (instead of the probability of one or more such events) greatly simplifies the formulation and makes the model more robust. As is usual in probabilistic analysis, it is easier to calculate expectations than probabilities. In PSHA, one calculates the expected number of occurrences as the sum of expected occurrences caused by many diverse earthquakes. The expectation of that sum will always be the sum (integral) of those expectations, even if future events are correlated in time, space, and size. There need not be any implicit or explicit assumption of Poissonian behavior, either in space or time in the

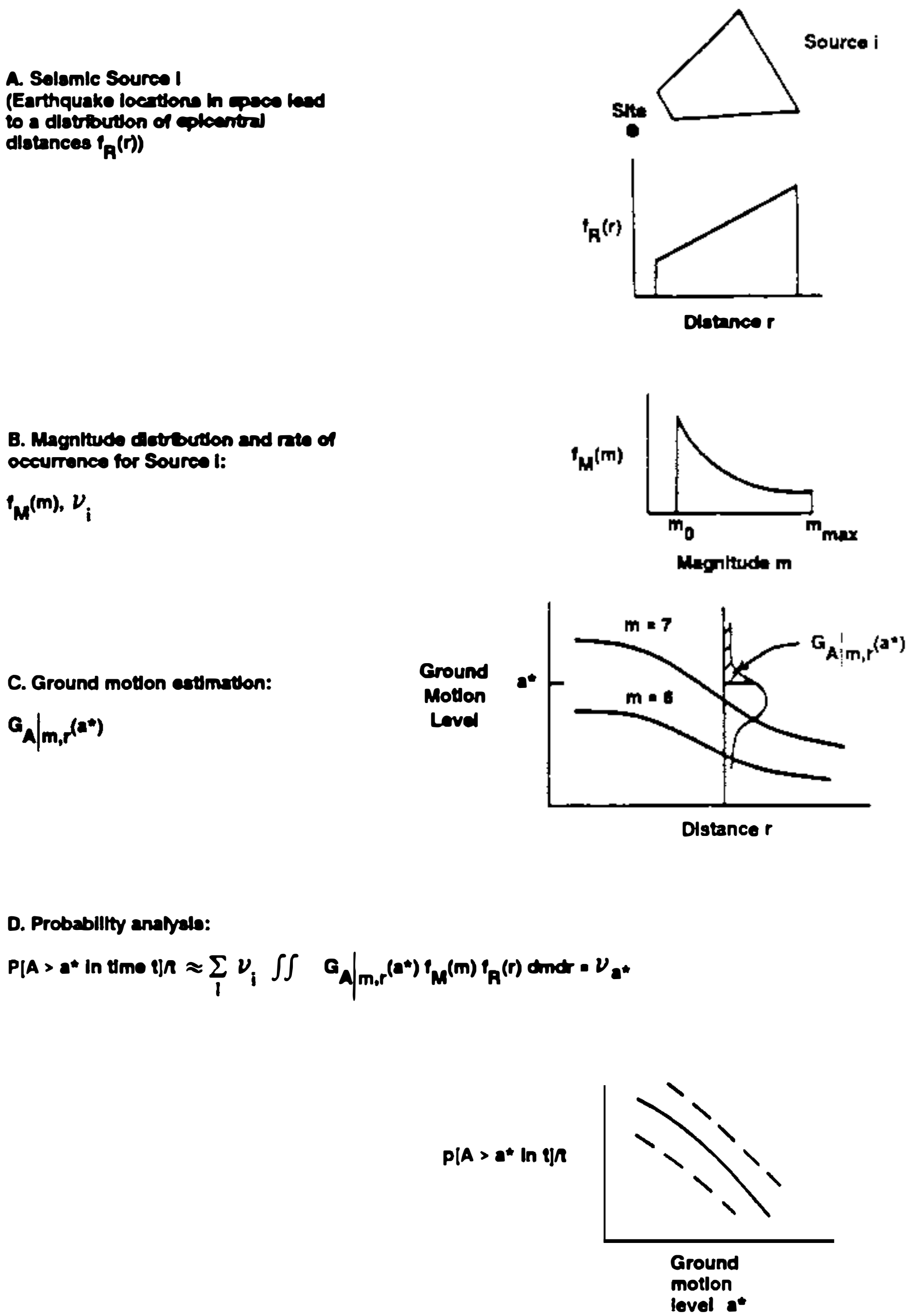

FIGURE 2.1: Steps involved in PSHA: A through C represent the three types of input required (seismic sources, magnitude distribution, and attenuation function), and D indicates the calculation of seismic hazard. (Seismic Owners Groups and Electric Power Research Institute, 1985.) Reprinted by permission from Electric Power Research Institute.

analysis. Virtually any model of future earthquake occurrence, including spatial, temporal, and size dependence, can be accommodated.

The analysis of seismic hazard is not limited to ground-motion amplitudes, whether characterized by scalars or vectors. Probabilities of fault displacement can be treated in an analogous fashion to that shown in Figure 2.1, substituting for the attenuation equation, a function that relates displacement to earthquake size. This type of analysis would be appropriate for a facility that crosses a fault where loss could occur if the fault displacement exceeds certain bounds. Also, direct estimates of soil liquefaction or landslide probabilities can be made, as long as the behavior of the soil can be directly related to earthquake size and distance as in Figure 2.1C. These are important, special applications that are not addressed explicitly in this report, but to which the general comments made herein about PSHA apply.

TYPES OF SEISMIC HAZARD ANALYSIS

In order to categorize PSHA and to evaluate it in the context of other methods of estimating earthquake hazards, we consider five types of analyses that reflect current usage.

Type I: Deterministic Seismic Hazard Analysis

The essential feature of deterministic seismic hazard analysis (PSHA) is that one or more earthquakes are selected with only implicit consideration of their probabilities of occurrence. One example is the tectonic province procedure currently used for nuclear power plant sites in the eastern United States, in which the largest Modified Mercalli Intensity in the province is identified, and then assumed to occur at the site. A second example is the assignment of a maximum credible earthquake with specified magnitude and at a specified distance. A third example is the identification of a "characteristic" earthquake on a fault segment with specified source parameters, which enables seismologists to predict strong ground-motion. Ground-motions obtained by Type I analysis range in sophistication from peak values obtained from attenuation relations, to complete seismograms that may be either synthetic or selected from prior recordings under similar conditions. Probabilistic concepts enter in this analysis only in a simple form, such as scatter about a mean ground-motion estimation curve.

Type II. Semiprobabilistic Seismic Hazard Analysis

As in Type I analysis, a semiprobabilistic seismic hazard analysis identifies one or more specific earthquakes. In this case, however, the probability of occurrence is an explicit consideration in the selection of the earthquake. For example, the maximum probable earthquake on a fault might be defined as an earthquake with a 100-year recurrence period. Ground-motions from the design earthquakes are determined in the same manner as in Type I analysis.

Type III. Single Model PSHA

A single model PSHA differs sharply from the Type I and Type II analysis techniques because in this case specific earthquakes are not identified. Instead, a curve is produced that gives the annual probability that given levels of a ground-motion parameter will be exceeded at the site of the structure. The curve is produced as the sum of contributions from all possible events.

Type III is called single model PSHA because it employs only one model for the distribution of earthquake locations and magnitudes, and one model for the relationship of the ground-motion parameter to the magnitude, distance, and site characteristics. (Figure 2.1D shows one result from a Type III analysis.)

A paper by Algermissen et al. (1982) gives an example of Type III analysis. Methods of PSHA that rely on historical seismicity must fall into this category or Type IV.

Type IV. Multiple Model PSHA

Often scientists are uncertain about appropriate models to use for the spatial distribution and occurrence rates of earthquakes and for the attenuation of the ground motion with distance. Under this circumstance, an appropriate procedure is to consider alternative models and to calculate the hazard curve for each of these models, as illustrated in Figure 3.2 in chapter 3. The variability of results in Figure 3.5 illustrates the range of uncertainty in the seismicity and attenuation models. To quantify the uncertainty on the hazard, multiple model PSHA assigns a probability to each model typically based on subjective probability. Examples of Type IV analyses are the Seismic Owners Group and Electric Power Research Institute (1985) and Bernreuter et al. (1985) studies.

Type V. Hybrid Procedure

Combinations of techniques might be desirable in a given situation. One useful hybrid method uses a Type III or IV PSHA to characterize ground-motion probabilities and identify individual earthquakes that contribute the most to the seismic hazard, and then uses deterministic procedures to derive more detailed characteristics of the seismic hazard, including time histories of ground motion, than are available from a typical PSHA. This hybrid procedure can more effectively take advantage of recent advances in geological and seismological observations and physical modeling of the earthquake source, wave travel path, and site effects.

TYPICAL APPLICATIONS

A common application of PSHA derives annual probabilities of exceedance for a scalar representation of seismic shaking, typically peak ground acceleration, peak ground velocity, or response spectral amplitudes. As examples of the input for a PSHA, Figure 2.2 shows a set of earthquake sources (faults) for the San Francisco Bay region, and Figure 2.3 illustrates a set of seismogenic sources for the eastern part of the country. A typical, though not necessary, assumption for seismogenic sources is that the mean activity rate per square kilometer is constant within any one source. For faults, a common definition for a continuous fault zone is that the mean rate of activity per kilometer of fault length is constant. Also, the characteristics of the magnitude distribution are usually assumed to be the same over any one source or fault.

Figure 2.4 shows a typical set of attenuation functions used for PSHA in California. Some California attenuation functions are based simply on regressions using empirical data; others are based on more theoretical analysis. Equations derived for California by different authors often are similar at large source-to-site distances where data are abundant. At near-source distances, or in the eastern United States, data are sparse and estimates from different equations may differ substantially. Figure 2.5 shows a typical set of results from a Type IV PSHA displaying the expected number of events (or probability of that event) in any one year as a function of the peak ground acceleration at the site. The results also show uncertainty in seismic hazard, a product of the uncertainty in the input.

HISTORICALLY BASED SEISMIC HAZARD ESTIMATION

It is often desirable to conduct a set of more nearly empirical estimates of seismic hazard to verify, to the degree possible within the historical record, the estimates made by the analytical method just described. As illustrated in Figure 2.6, this is done in a straightforward manner. The catalog of historical earthquake magnitudes and locations is used to generate a catalog of estimated ground motions at the site of interest. This list of data is then processed in a familiar manner, for example, the way one commonly processes windspeed data or flood data. These results represent a nearly purely empirical estimate of the seismic hazard curve at a site. The estimate does not require assumptions about seismic sources and magnitude distributions, but requires the adoption of an empirical

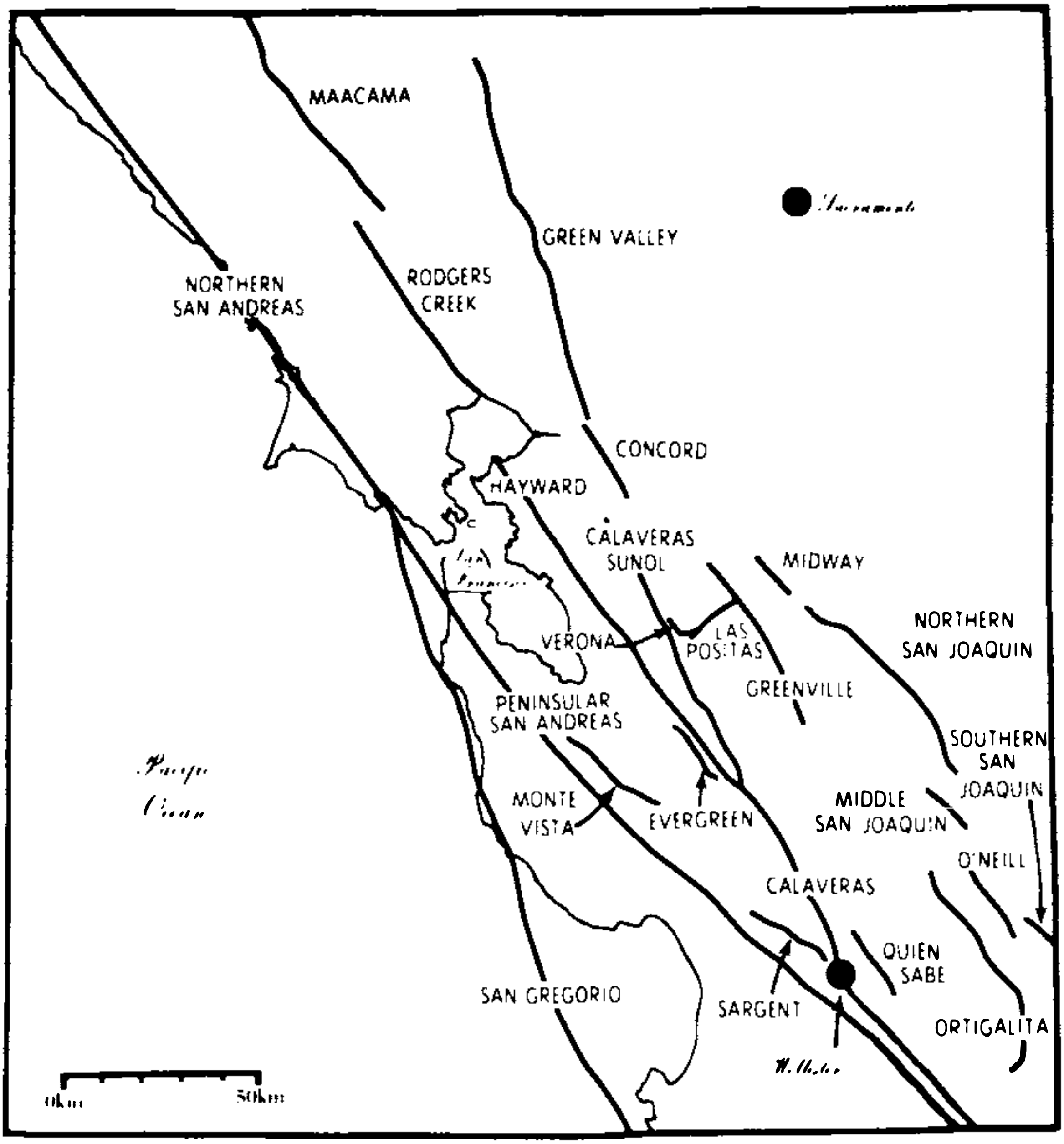

FIGURE 2.2 **Faults in the San Francisco Bay area (McGuire and Shedlock, 1981). Reprinted by permission from Seismological Society of America.**

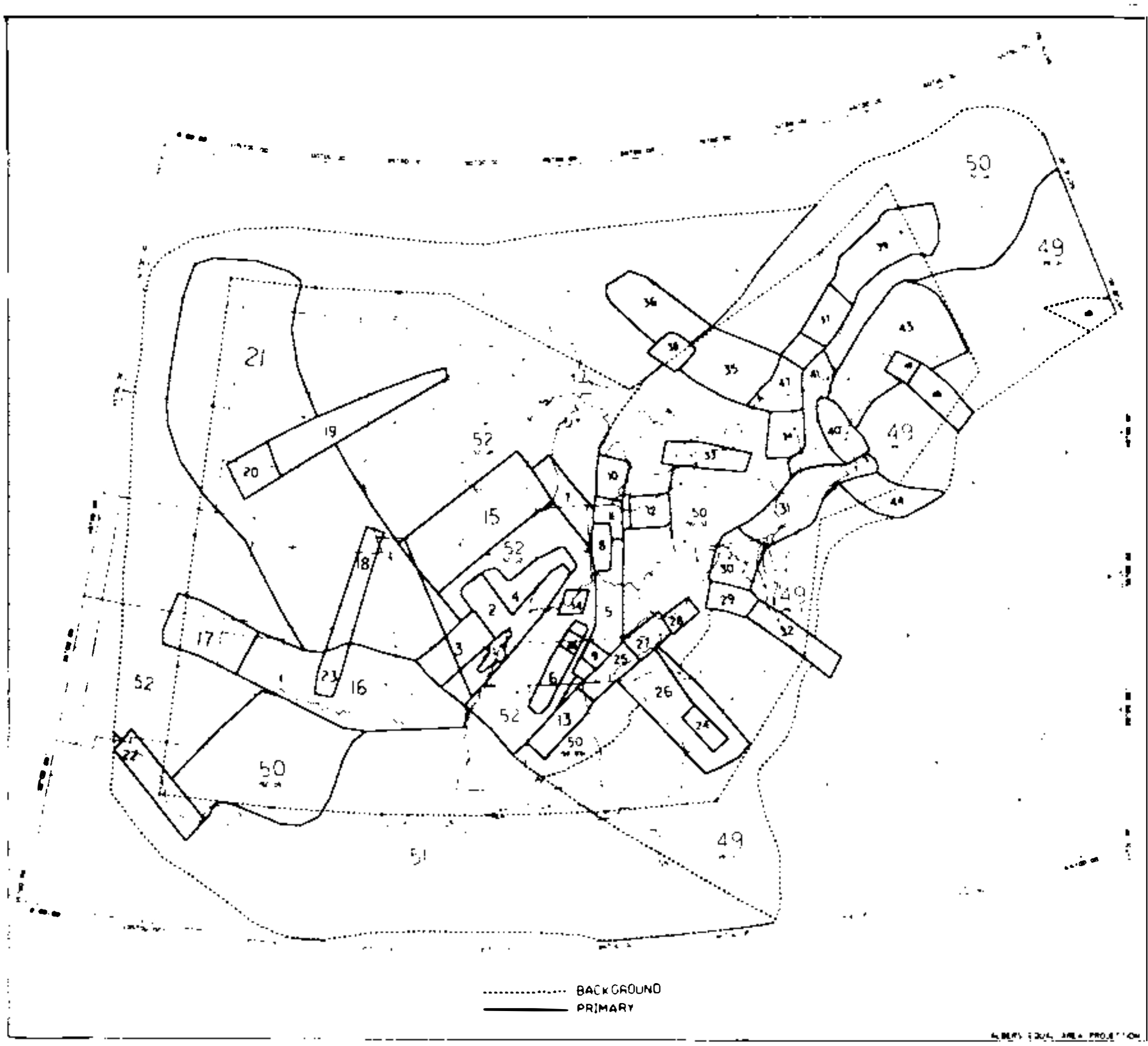

FIGURE 2.3 Example of source zonation in the eastern United States. Numbers indicate source zones. (EPRI, Seismic Hazard Methodology for the Central and Eastern United States, July 1986). Reprinted by permission from Electric Power Research Institute.

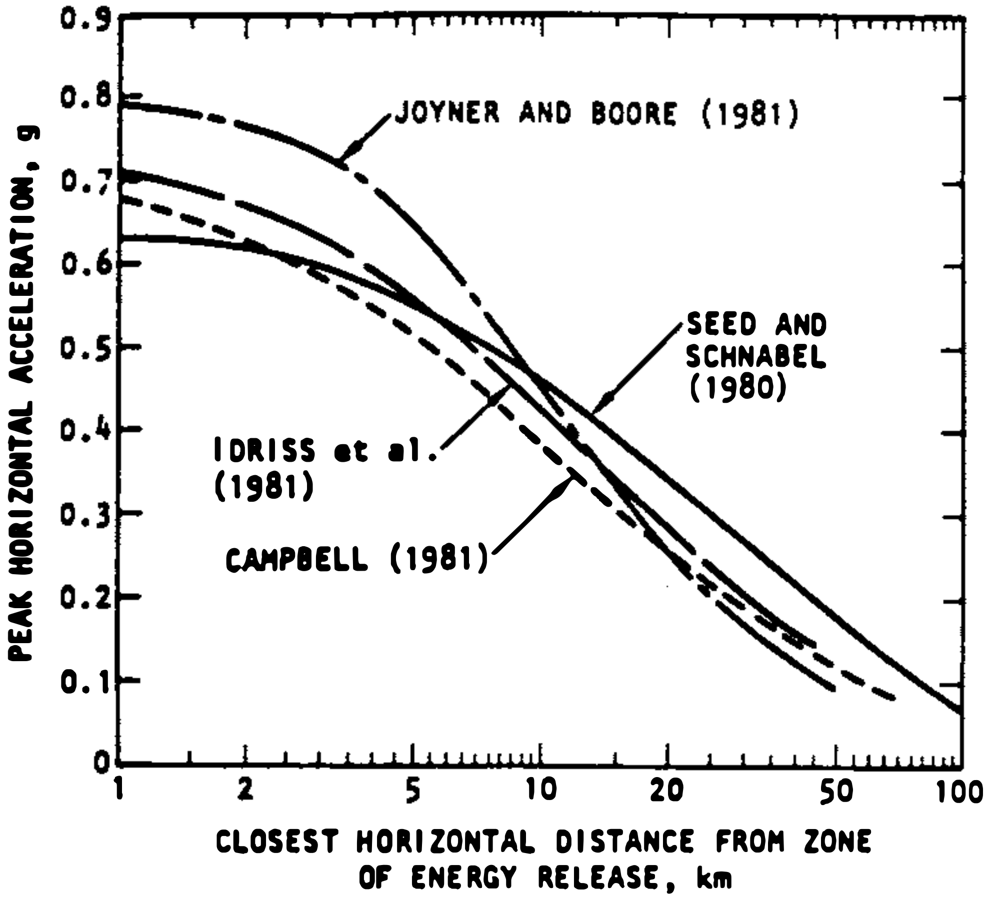

FIGURE 2.4 Typical California attenuation curves for M_s = 7.5. (Seed and Idriss, 1982). Reprinted by permission from the Earthquake Engineering Research Institute.

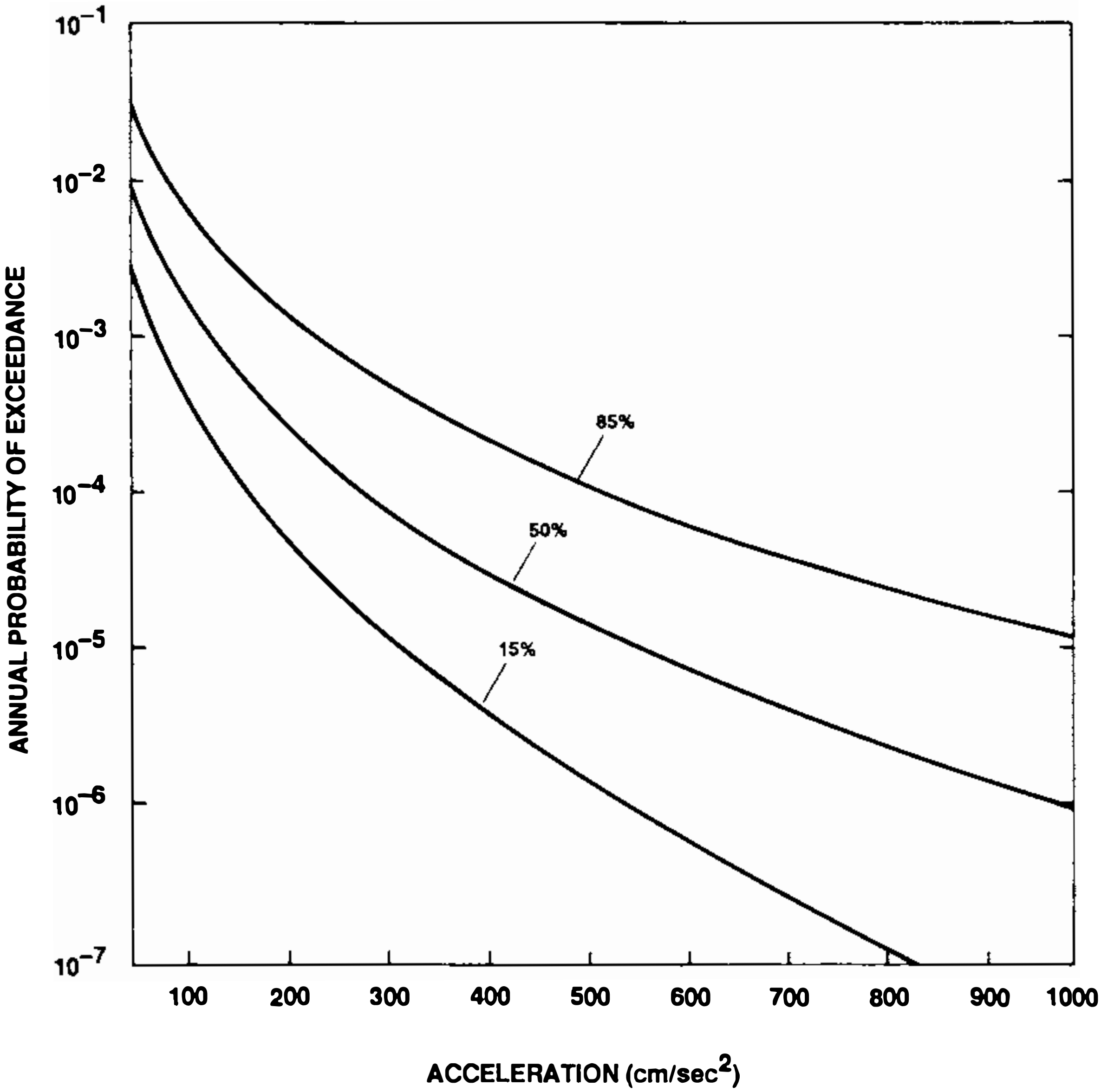

FIGURE 2.5 Constant percentile hazard curves (CPHC) over all experts (Bernreuter et al., 1985). Shows typical set of results from a Type IV PSHA displaying expected number of events in any one year as a function of peak ground acceleration at the site. Reprinted by permission from Lawrence Livermore National Laboratory for the University of California and the Department of Energy.

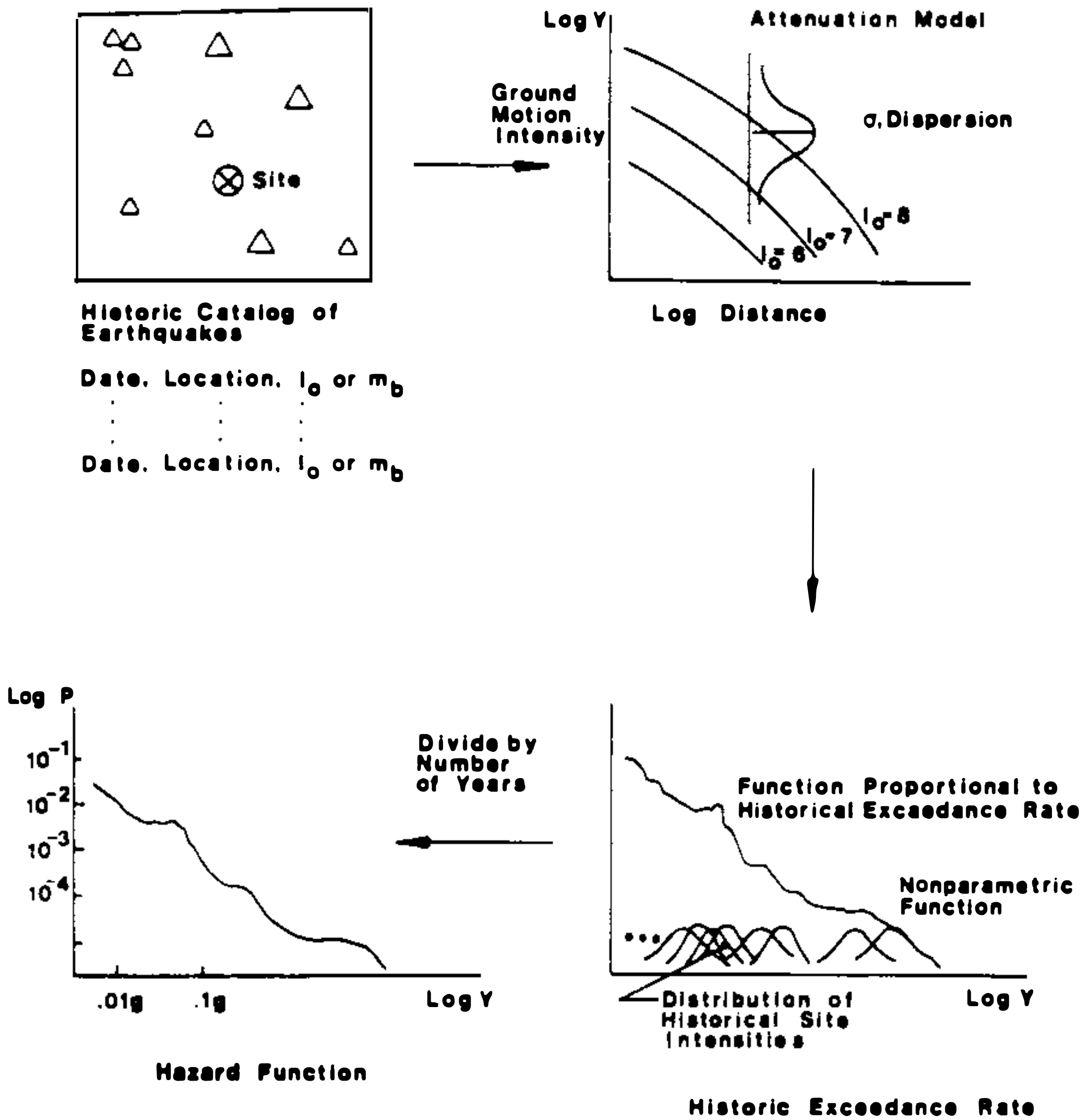

FIGURE 2.6 Steps involved in the (nonparametric) historic method. (Veneziano et al., 1984). Reprinted by permission from the Electric Power Research Institute.

or theoretical ground-motion prediction model and a correction for earthquake catalog incompleteness, not always a trivial task.

One may be confident in these historical hazard estimates at annual probability levels as low as perhaps 10^{-2}, provided the catalog is 200 to 300 years long. Annual probabilities of 10^{-2} are of interest in insurance studies, in regional planning analyses, and in the development of design criteria for conventional buildings. However, for many critical structures (e.g., dams and nuclear power plants), estimates of annual probabilities as low as 10^{-3} or 10^{-4} are required. In these instances the historical analysis provides a way of evaluating or calibrating the analytical model at levels above 10^{-2}. This evaluation may be important if, for example, the analytical model's estimates are systematically too high at 10^{-1} and 10^{-2}; one might expect its estimates to be high at lower probabilities as well, and one can seek the source of the model's error and correct it.

ANALYSIS OF UNCERTAINTIES

It is important in any estimation of low probabilities (be they structured or purely empirical estimates) to make a statement about the degree of confidence in the results. A common way to examine uncertainty is to conduct sensitivity studies, varying the input parameter values and model assumptions to see their impact upon the low-probability, high-acceleration results. Reviewing the sensitivity of hazard to changes in the parameter values can lead to qualitative conclusions regarding the uncertainty in analysis results.

This basic process can be formalized and quantified in uncertainty analysis or uncertainty propagation schemes of the type now in common use in seismic hazard analysis. As illustrated in Figure 2.7, such an uncertainty analysis, called a logic tree, considers a spectrum of values for each of the input parameters, a spectrum of functional forms for the attenuation law, and a spectrum of model alternatives with respect to the seismic sources. Each node at the right end of the tree represents a unique seismic hazard analysis for a specified set of assumptions. The second step assigns degrees of confidence to the individual parameter values and/or model alternatives. In principle, this can be done using formal statistical methods for some of the parameters; e.g., the slope of the magnitude frequency plot. (Even that, however, may prove difficult because there is often more uncertainty in the catalog completeness process than there is in the more familiar, formal line-fitting procedure). For other assumptions, such as alternative attenuation laws or source zonations, relative weights or "degrees of belief" are assigned to each model to reflect the analyst's or the profession's relative confidence in these alternatives. Methods of uncertainty assessment that have been used in practice include a single analyst's (or team of analysts) uncertainties, a single analyst's attempt to reflect the profession's uncertainty, or "voting by proxy," i.e., counting the number of

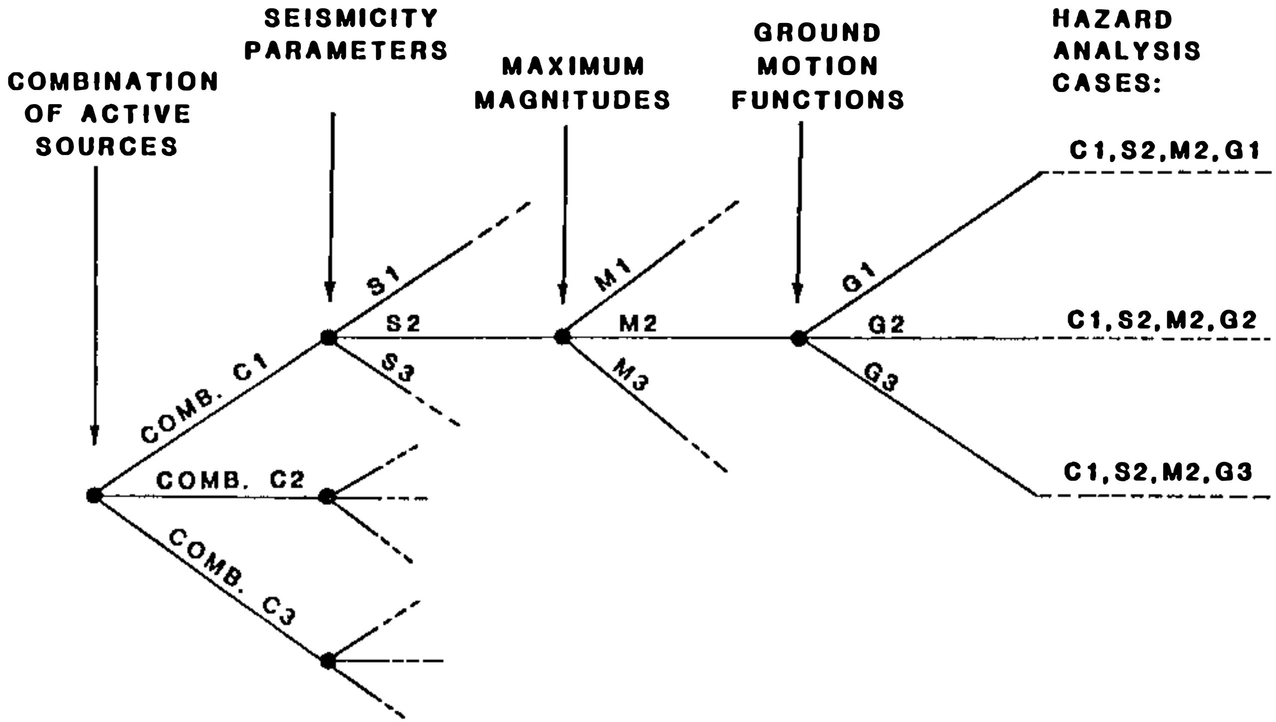

FIGURE 2.7 Example of logic tree format used to represent uncertainty in hazard analysis input. Each branch has an assigned weight and the sum of weights on branches attached to any node is unity (McGuire, 1986). Reprinted by permission from R. K. McGuire.

individual opinions expressed in published technical studies that favor each alternative hypothesis. It should be noted that the use of opinions of multiple analysts or experts is still somewhat controversial, although several large PSHAs have adopted this approach (e.g., Seismic Owners Group and Electric Power Research Institute, 1985; Bernreuter et al., 1985).

Once the results of individual hazard analyses and the weights associated with these analyses are available, they can easily be processed to make them more amenable to inspection. For example, fractile hazard curves for a range of ground-motion levels represent the confidence that the hazard does not exceed specified levels. Curves of this type are illustrated in Figure 2.5.

PRESENTATION OF RESULTS

Results of a PSHA are used by engineers, regulators, code writers, disaster planning and response organizations, risk managers, and insurance entities, for a variety of purposes. The requirements of PSHA for these users are varied.

To design and estimate damage to buildings, residences, and standard commercial facilities, a scalar characterization of ground motion and a minimum representation of uncertainty are often sufficient. A standard spectral shape can be anchored to the chosen scalar to obtain approximate, equivalent results for a range of structural frequencies of interest. Typically, ground motions with annual probabilities in the range of 10^{-1} to 10^{-3} are of interest to these facilities.

For critical facilities (nuclear power plants, large dams, and industrial and military installations involving toxic, dangerous, expensive, or sensitive operations), a vector representation of ground motion is often required, including ground-motion energy at multiple frequencies and duration of strong shaking. For these critical systems, nonlinear models of structure, building and/or equipment response to strong shaking may be used; appropriate, realistic input motions for these models are required, and the PSHA must give sufficient information so that realistic motions can be derived, for annual probability levels of 10^{-3} to 10^{-4} or lower. For these facilities a full and accurate quantification of uncertainty is also often required, in order to account explicitly for uncertainty in hazard results when making decisions to mitigate seismic risk.

A PSHA has the ability to represent seismic hazard for all of these applications, as long as the requirements are understood and specified. A more detailed description of the needs of various users of PSHA is given in chapter 3.

MISCONCEPTIONS ABOUT PSHA

A common misconception about PSHA is that historical data--over several hundred years or less--are extrapolated to estimate annual probabilities of 10^{-3} and lower. In fact, one gains the ability to predict low probabilities, (e.g., 10^{-3} and 10^{-4}), by segregating the problem into components; theory and additional data can be brought to bear on each component, allowing reliable probability estimates on the order of 0.5 to 0.1. The ultimate answer of 10^{-3} or 10^{-4} is obtained by combination (a product) of the larger and better constrained probability values. Thus, the method uses a general type of analytical model in which the problem is disaggregated into pieces that are better understood and for which a broad sample of data, experience, and other information may be available. Those pieces are then reaggregated through the model's structure to obtain a solution. As an example, 200 years of historical earthquake data in a region might suggest that the annual probability of an earthquake (above magnitude 5) is 0.1. Experience from other regions might indicate that, if an earthquake occurs, it will exceed magnitude 6 with probability 0.1. The historical distribution of epicenters might indicate that, with probability 0.1, any randomly selected earthquake will occur within 30 km of our site. Finally, experience in California might suggest that abnormally high ground shaking might occur at our site, because of focusing and path effects, with probability 0.1. We might thus logically conclude that the probability of strong shaking is 10^{-4}, when the local historical data are available for only 200 years. (A PSHA, of course, multiplies over many such combinations of events to calculate their probabilities, but the concept is similar to that illustrated above.) The strength of this approach, of course, is that more data and information that affect the hazard estimate are brought to bear on the detailed modeling problems. This final calculation may be sensitive to the input assumptions used in the analysis, but a proper evaluation and quantification of uncertainty will make this sensitivity knownto the user.

A second misconception relates to the representation of uncertainty. As discussed elsewhere in this report, the scientific uncertainty in assumptions critical to a PSHA are large in many parts of the country (often leading to an order of magnitude uncertainty in probability representing one standard deviation). This is not a fault of PSHA, but a result of uncertainty in what geologic features will cause future earthquakes, how often those events will occur, and what ground motions will result. Other, more deterministic analyses will not reduce those uncertainties; in fact, such analyses usually do not display them at all. An uncertainty analysis conducted as a part of a PSHA can properly represent these uncertainties, thereby allowing optimum decisions to mitigate earthquake hazards and allowing optimum allocation of natural and human resources.

Another misconception about PSHA is that it always allows users to justify lower design levels. There is nothing inherent in a probability analysis that suggests an acceptable level of risk; any specific application can only quantify the probability associated with future events. In comparing those probabilities for certain engineering or planning decisions with decisions in other sectors, the analyst may come to the conclusion that past practice has been relatively conservative or unconservative, depending on the results of the comparison.

3

ISSUES AND DISCUSSIONS

The panel developed a questionnaire and the user community was sampled about issues related to PSHA (see Appendix B). Guests were invited to panel meetings for discussion of specific topics. Chapter 3 was designed to deal with the main issues involving PSHA and its use. These issues are presented in six major sections of this chapter as follows: the needs of the users with respect to how PSHA is used; how earth science information is incorporated into PSHA; uncertainty(ies) and instability(ies) in the results of the analyses; testing PSHA and liabilities that might apply to PSHA analysts; possible loss of information by the aggregation or lumping together of many earthquakes in PSHA; and how PSHA can be used by decision makers.

NEEDS OF THE USER

The results of PSHA are hazard evaluations, commonly illustrated as curves with associated uncertainties. For decision making, the user needs to consider the implications of those results on loss of life and property for his or her applications, and needs to assess the costs and consequence of various strategies to mitigate seismic hazard. Such assessments may range from intuitive judgment to sophisticated risk and decision analyses.

The panel identified four classes of PSHA users whose needs depend on the required seismic safety level and lifetime of the facility of concern:

1. Designers, code writers, regulators, and owners of conventional facilities are interested primarily in seismic hazard estimation for the annual probability of exceedance in the range from 10^{-2} to 10^{-3} (i.e., the ground motion that is exceeded with annual probability of 0.01 to 0.001). These users usually do not require explicit display of uncertainty. However, agreement on the implicit treatment of uncertainty in the hazard estimates among practitioners is desirable for a stable and logical basis for decision.

2. Critical facilities, such as nuclear power plants, dams, and liquified natural gas (LNG) facilities typically have a lifetime of 30 to 50 years. Owners and regulators of these facilities would like to

have stable seismic hazard estimates in the annual exceedance probability range of 10^{-3} to 10^{-4}. Some hazard analyses for critical facilities may require estimation at levels that may extend as low as 10^{-6} annual exceedance rate. Higher annual levels of hazard may be tolerable during construction or for facilities with very short exposure times. Because considerable uncertainty exists in such analyses, predictions for critical facilities require the inclusion and display of their uncertainty, so as not to lead decision makers into inferring a high degree of accuracy.

3. Owners and regulators of long-term hazardous waste repositories desire hazard estimations at 10^{-2} to 10^{-4} for facility lifetimes of 10,000 years, i.e., the annual exceedance probabilities range from 10^{-6} to 10^{-8}. Hazard estimates for these lifetimes, based only on the short historical record are highly uncertain and probably not appropriate. Such long exposure times may require qualitatively different assumptions about the earthquake processes than those at comparable annual probability levels for short lifetimes (e.g., 50 years). Paleoseismic data and other techniques under development provide a credible basis for hazard evaluation at some sites and promise wide applicability in the future.

4. A variety of other users, including federal, state, and local officials, the general public, the news media, and disaster response organizations, have important special needs for seismic hazards evaluation. These users are increasingly willing to accept information about seismic hazards in a probabilistic format.

Ground-Motion Parameters of Interest

Approaches to describing ground-motion parameters with increasing levels of technical detail include the following:

- Intensity (qualitative descriptions of ground-motion effects);
- Peak acceleration, velocity or displacement;
- Duration of strong shaking;
- Response spectra; and
- Ground motion time histories.

(See the glossary, Appendix D, for descriptions of these parameters.) The ground-motion parameters of interest strongly depend on the user of the PSHA.

For general seismic risk or loss estimation studies that cover large areas and/or a large number of different facilities, the primary need is to have a single, simple measure of ground motion that is capable of expressing damage potential throughout the region and for the diverse types of facilities. The Modified Mercalli intensity is currently used for this purpose, although peak or effective ground acceleration or ground velocity has been used to a lesser extent.

For local geological hazards, such as seismic-induced landslides or liquefaction, prediction of a single ground-motion parameter is insufficient. For these uses, both a ground-motion amplitude and a duration parameter are needed. Amplitudes can be described by either leak ground acceleration or velocity. Duration can be defined by the duration of strong shaking or the number of near peak or equivalent peak excursions. In some instances, both the amplitudes and duration parameter have been combined into a single effective amplitude parameter, such as effective acceleration, coupled with some normalized duration. For lifelines crossing active faults, the parameter of interest is the amount of relative displacement across the fault.

For the design or evaluation of a specific facility at a specific site, more information is generally required. A useful ground-motion description for seismic design of facilities or seismic risk studies is in terms of a response spectrum showing damped spectral response versus natural frequency. Such a response spectrum can display either spectral acceleration, spectral velocity, or spectral displacement. The damping range of primary interest for damage assessments is from 5 percent to 20 percent of critical damping. However, some complexities develop when results of a probabilistic seismic hazard study are displayed in terms of response spectra. Sufficient information cannot be displayed in a single plot. Figure 3.1 presents an example plot of a best-estimate uniform hazard spectra that displays the best-estimate spectral response versus natural period for several different recurrence intervals. Thus, this plot shows how spectral response varies with recurrence interval or annual frequency of exceedance. However, this plot does not display any information on uncertainty in these spectral responses. Alternately, for a given recurrence interval one could display mean, median, and uncertainty bands on spectral response in a single plot. However, now, one would have to provide multiple plots to cover a range of recurrence intervals. Even so, multiple plots of uniform hazard spectral response, each displaying median, mean, and uncertainty information on spectral response for different recurrence intervals or annual frequencies of exceedance, are one way of providing the minimum ground-motion parameter information required.

An alternative and more commonly used approach is to provide plots of one or two ground-motion parameters, such as peak ground acceleration or peak ground velocity, versus annual frequency of exceedance. Such plots are substantially easier to develop than uniform hazard spectra plots and enable the full range of uncertainty information and annual exceedance frequency information to be displayed on a single plot. However, to be useful in seismic design or seismic risk studies, one must then construct a design spectrum from the ground motion parameter(s) used in the PSHA, because the spectral shape is likely to be different for ground motions in the 10^{-2} to 10^{-3} annual exceedance frequency range than for ground-motions in the 10^{-4} to 10^{-6} annual exceedance frequency range. Thus, a single standard uniform hazard response spectrum or design spectrum shape is not likely to be applicable throughout the entire annual frequency of exceedance range. For this reason it is preferable to construct the spectrum from at least two ground-motion parameters, representing the frequency range of interest, so that changes in spectral shape caused by effects of different earthquake magnitudes and distances at different probability levels will be reflected.

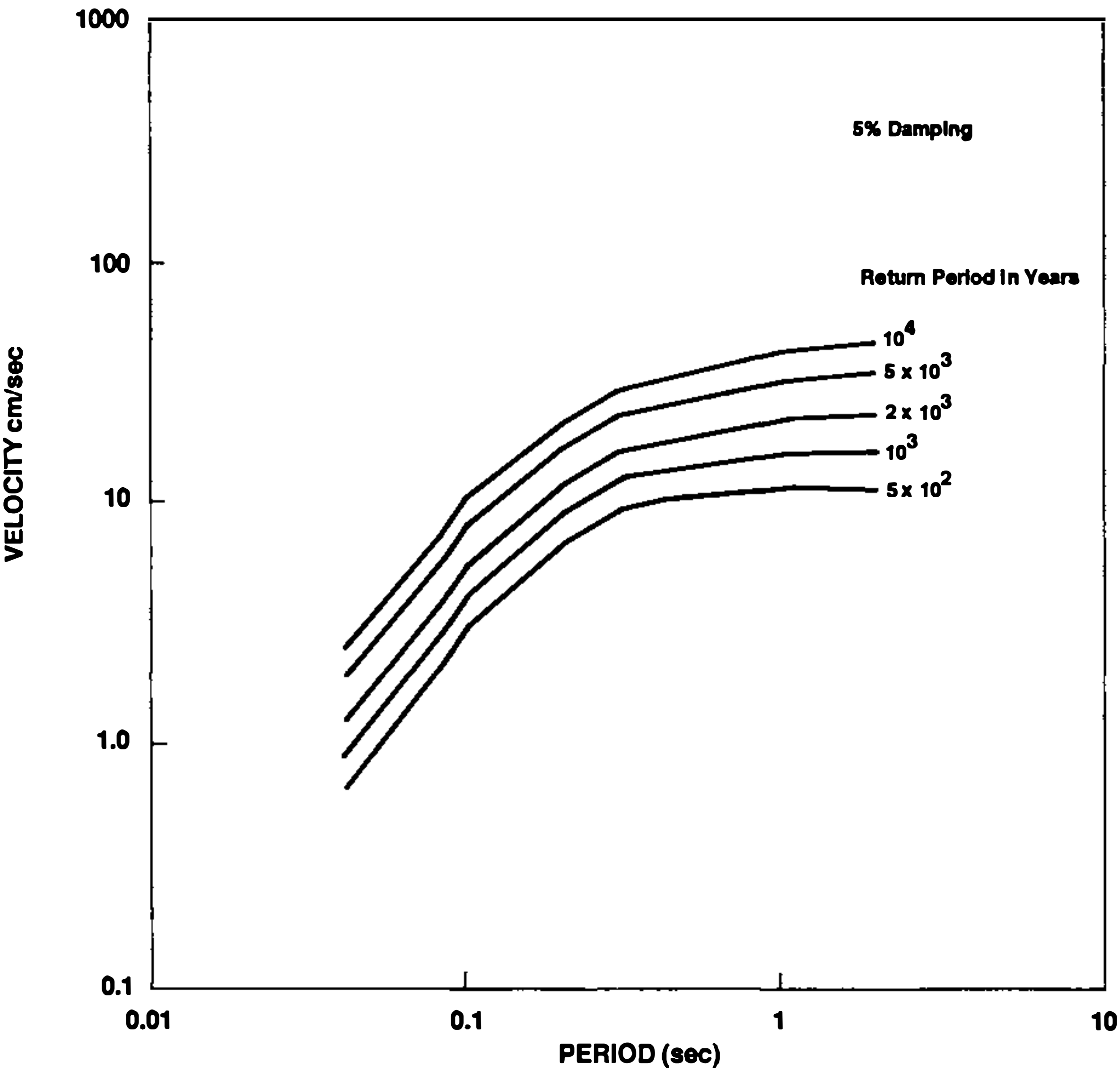

FIGURE 3.1 Example of best-estimate uniform hazard spectra curves (Bernreuter et al., 1985). Reprinted by permission from Lawrence Livermore National Laboratory.

When this alternative approach of specifying a standard response spectrum and then providing a probabilistic hazard prediction on only one or two ground-motion parameters is used, the question always arises as to which are the most appropriate ground-motion parameters to use. For conventional structures, probably the best ground-motion parameter with which to scale the standard response spectrum is the spectrum intensity, peak ground velocity, or response spectrum amplitude at a period of about 1 sec.

If one is only concerned with very stiff structures such as those associated with nuclear power plants in which natural frequencies are nearly always in excess of 2 Hz, then the ground motion parameter of primary interest should be related to ground acceleration (Kennedy et al., 1984). Both "effective" peak and instrumental peak accelerations have been suggested and used for this purpose.

No matter which approach is chosen, for detailed evaluation of a specific facility, the probabilistic seismic hazard predictor should always provide a description of the ground motion in terms of spectral response either through the use of uniform hazard spectra versus annual frequency of exceedance or through the use of a standard spectrum scaled by one or more ground-motion parameters, which are defined versus annual frequency of exceedance.

For specific facility evaluations, the ground motion at a particular site is often expressed in terms of two orthogonal horizontal ground-motion components and one vertical component. Generally, the probabilistic seismic hazard is described in terms of either the average of the two horizontal components (such as mean peak instrumental acceleration) or in terms of the larger of the two horizontal components (such as peak instrumental acceleration). It is necessary for the hazard prediction to define clearly whether the average or the larger component is being predicted. It is also desirable for the predictor to provide estimated ratios between the larger and average horizontal component, and between the vertical and horizontal component to be used with the hazard prediction.

In most instances, a description of the ground motion in terms of spectral responses for two orthogonal horizontal ground motion components and one vertical component is sufficient. However, in some instances the user might require an ensemble of "realistic" ground-motion time histories. In this instance, the user should define the annual exceedance frequency range of greatest interest (such as 10^{-2} to 10^{-3} or 10^{-4} to 10^{-5}). The probabilistic seismic hazard analyst should then provide an ensemble of "realistic" ground motion time histories that are representative of ground motions from earthquake magnitudes and hypocentral ranges, which contributes most to the seismic hazard within the annual exceedance frequency range of greatest interest.

The hazard prediction must define the location at which the hazard is being defined for the site of interest. Is the hazard being defined (1) at the free ground surface for the actual site conditions, (2) at the free ground surface for some generic rock or stiff soil site, or (3) at a bedrock layer below the ground surface?

In conclusion, for many users, a useful probabilistic seismic hazard prediction must provide substantially more information than just the magnitude of a single ground-motion parameter versus annual frequency of exceedance.

Annual Probability Levels of Interest

Facilities might be categorized as follows (Joint Departments of the Army and Air Force, USA, 1985).

I. Hazardous critical facilities, such as nuclear power plants, dams, and LNG facilities.
II. Essential facilities that are necessary for post-disaster recovery and require continuous operation during and after an earthquake.
III. High risk facilities where the primary use is for assembly of a large number of people or for people who are confined or where services are provided to a large area or large number of other buildings.
IV. Less vital facilities, not falling into any of the above categories.

Facilities classified as categories II, III, and IV tend to have similar design procedures but with differing levels of conservatism embedded into the design. The seismic design procedures for Category I facilities tend to be more complex and rigorous.

In the past, category II, III, and IV facilities located in California, Nevada, and Washington were designed for the seismic hazard defined in the Uniform Building Code (UBC) (International Conference of Building Officials, 1982). Generally, other regions of the United States either have used this UBC seismic hazard definition or have ignored seismic design. The UBC seismic provisions historically have been based on designing for the largest earthquake that has occurred in a given region over the last 200 years. The most recent version of the UBC does adopt a PSHA and, therefore, does consider the relative probability of occurrence in various parts of the country. However, within the last 10 years, there has been considerable interest in developing a national seismic design code. Proponents have suggested that a seismic design code would be more widely accepted if the seismic hazard provisions of this code were based upon a consistent uniform annual probability of exceedance for all regions of the United States. Several probabilistic based seismic hazard provisions have been proposed (Algermissen et al., 1982; Joint Departments of Army and Air Force USA, 1985; Applied Technology Council, 1978). Canada has adopted this approach (National Research Council of Canada, 1980). The suggested annual probability of exceedance for the design seismic hazard level differ somewhat between proposed codes, but all lie in the range of 10^{-2} to 10^{-3}. For instance, ATC-3 (Applied Technology Council, 1978) has suggested the design seismic hazard level should have about a 10 percent probability of exceedance level in 50 years, which corresponds to an annual exceedance probability of about 2 x

10^{-3}. The Canadian building code (National Research Council of Canada, 1980) uses 1×10^{-2} as the annual exceedance level for the design seismic hazard definition. The proposed Department of Defense tri-services seismic design provisions (Joint Departments of Army and Air Force, USA, 1985) suggests for category II facilities a dual level for the design seismic hazard. Such facilities should remain essentially elastic for seismic hazard with about a 50 percent probability of exceedance in 50 years or about a 1×10^{-2} annual exceedance probability and should not fail for a seismic hazard that has about a 10 percent probability of exceedance in 100 years or about 1×10^{-3} annual exceedance probability.

Thus, for conventional facilities (categories II, III, and IV), there is considerable interest among facility designers, code writers, and regulators to have probabilistic seismic hazard predictions within the annual probability of exceedance range of 10^{-2} to 10^{-3}. It should be noted that structures and facilities are conservatively designed for the defined seismic hazard so that the annual risk of severe damage is substantially less than the annual probability of exceedance of the defined seismic hazard used for design.

Nuclear power plants, which are category I facilities, are designed so that safety systems do not fail if subjected to a safe shutdown earthquake (SSE). The SSE is a deterministic specification of the expected ground motion at the site. It is derived from estimated ground motion of the largest historic earthquake within the tectonic provinces surrounding and including the site, or from estimated ground motions of earthquakes on active tectonic structures near the site.

Recent probabilistic hazard studies (i.e., Bernreuter et al., 1985; Seismic Owners Group and Electric Power Research Institute, 1985) have indicated that for plants in the eastern United States, the design SSE level generally corresponds to an estimated annual probability of exceedance on the order of 10^{-3} to 10^{-4}. Also, during the last 10 years, considerable interest has developed in estimating the seismic risk of these nuclear power plants in terms of annual probability of seismic-induced core melt or risk of early fatalities and latent cancer to the public. Many studies have been conducted on seismic risk of individual nuclear power plants. Because those plants are very conservatively designed to withstand the SSE, these studies have indicated that the seismic risk is dominated by ground-motions substantially greater than the SSE. Generally, these studies have indicated that the seismic risk is dominated by seismic hazards with annual probability of exceedance in the 10^{-3} to 10^{-6} range. The assessments of seismic risks made by these studies are only as good as the seismic hazard assessments at annual probability levels of 10^{-3} to 10^{-6}.

Thus, for category I facilities (such as nuclear power plants) there is considerable interest among facility owners and regulators in seismic hazard predictions within the annual exceedance probability range of 10^{-3} to 10^{-6}. Hazard estimates at these probability levels are subject to considerable uncertainty.

Display of Uncertainty

A typical seismic hazard analysis (SHA) for a particular site produces a set of potential seismic hazard curves of the type shown in Figure 3.2, which describes the annual frequency of exceedance versus some ground-motion parameter such as peak ground acceleration. This hazard analysis might display uncertainty by the use of multiple postulated curves based upon differing assumptions (such as shown in Figure 3.2). Alternatively, the hazard analysis might display uncertainty through the use of either a mean or median curve coupled with 15 percent and 85 percent confidence band curves (such as shown in Figure 3.3). In other instances, uncertainty is not displayed and only a single hazard curve is presented. Differing levels of uncertainty are incorporated into the development of such a hazard curve. Sometimes no uncertainty is incorporated and the hazard curve is developed from a single best-estimate attenuation relationship appropriate for each region. Alternatively, a single mean hazard curve might incorporate the variability of data about that predicted by a single best-estimate attenuation relationship or may also incorporate uncertainty in attenuation relationships, and possibly even uncertainties in seismological models. It should be noted that even within the 10^{-2} to 10^{-3} annual exceedance frequency range, the differences between predicted peak ground acceleration from such hazard curves that do and do not incorporate uncertainty often differ by a factor of about 2. At lower exceedance probabilities, this difference is even greater.

Because considerable uncertainty must exist in any seismic risk prediction dominated by seismic hazards with annual exceedance probability less than 10^{-3}, such risk predictions should always include and fully display their uncertainty, to avoid misleading decision makers to the belief that such predictions have undue precision. This requires that any seismic hazard prediction carried out for use in a seismic risk study of hazardous critical facilities should always include and fully display its uncertainty. As a minimum, such hazard predictions should provide mean and median predictions as well as some indication of uncertainty bands such as the 15 percent and 85 percent nonexceedance probability levels.

For the typical SHA, the primary need is to use the available several hundred years of historical earthquake data to predict ground-motion levels that have annual frequencies of exceedance between 10^{-2} and 10^{-3} for categories II, III, and IV, and between 10^{-3} and 10^{-4} and possibly 10^{-6}, for hazardous critical facilities (category I), over a rather limited number of future years (generally 50 years or less). Thus, there is no attempt to extrapolate a relatively short historical earthquake data base far into the future.

However, when one considers facilities, such as waste repositories, one must be concerned with the long-term storage of hazardous waste. In this instance, one may be interested in estimating the ground-motion level that has low frequency of being exceeded over times possibly as long as 10,000 years into the future. The need for estimating ground motion levels with less than 10^{-2} to 10^{-4} frequency of being

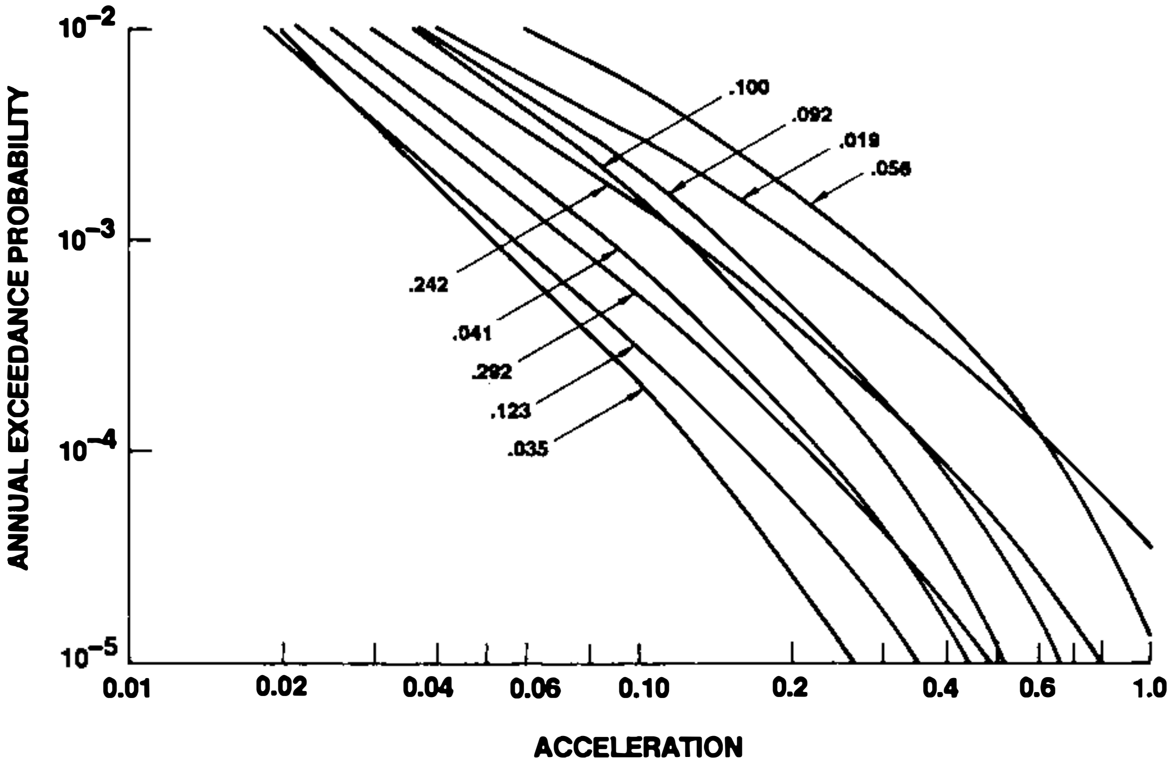

FIGURE 3.2 Typical seismic hazard analysis results for particular site. Number for each curve is weight assigned to analysis. Seabrook Station Probabilistic Safety Assessment. Reprinted by permission from Public Service Co. of New Hampshire (1983).

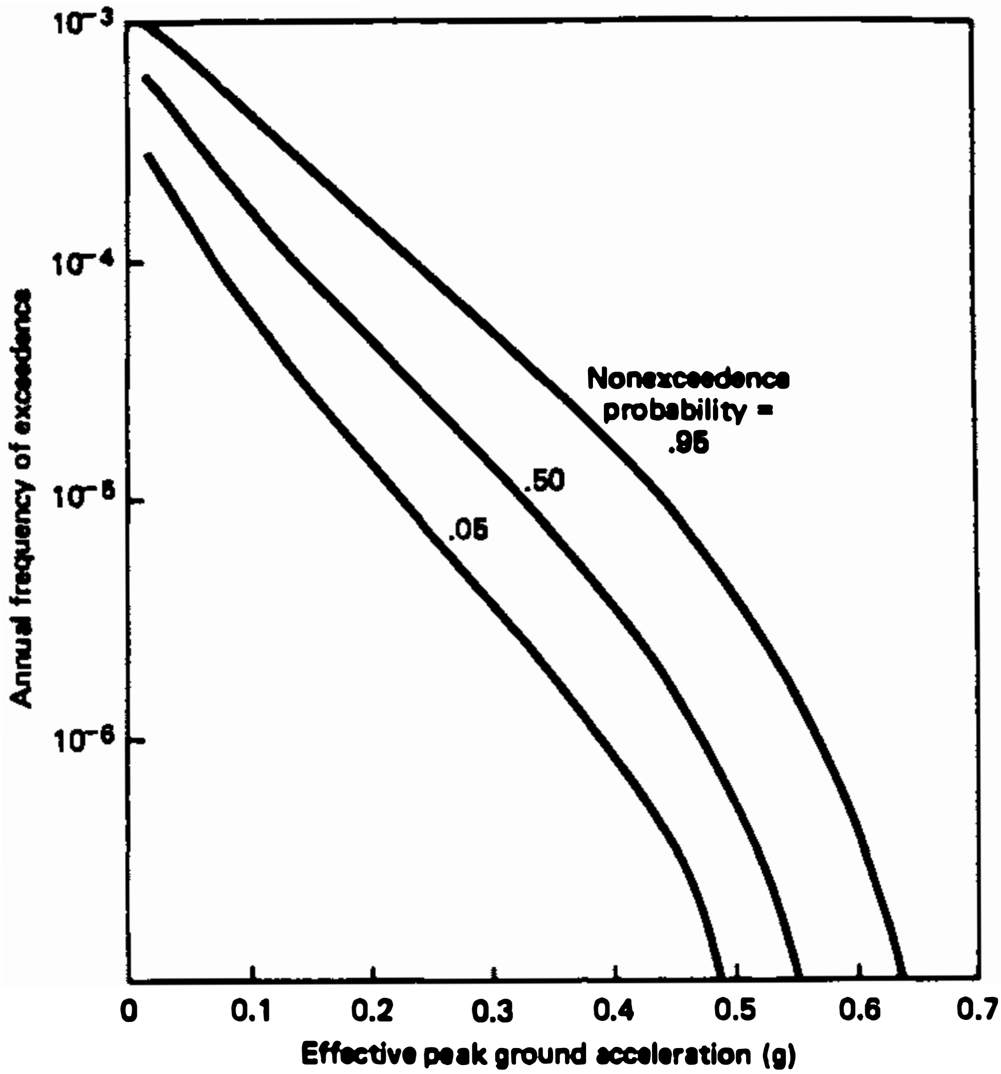

FIGURE 3.3 Seismic hazard curves for a hypothetical site (Office of Nuclear Regulatory Research, 1981).

exceeded in the next 10,000 years has sometimes been suggested. This estimate would correspond to an annual frequency of exceedance of 10^{-6} to 10^{-8}. Hazard estimates for these long exposure times based only on the short historical record are highly uncertain and should be used with caution. Such long exposure times may require qualitatively different assumptions about the earthquake processes than those at comparable annual probability levels for short exposure times (e.g., 50 years). Paleoseismic data and other techniques under development provide a credible basis for hazard evaluation at some sites and promise wide applicability in the future.

HOW PSHA CAPTURES EARTH SCIENCE INFORMATION

Earth science information is the foundation for any seismic hazard assessment. It is in the Earth that earthquakes are generated, and it is through Earth materials that seismic waves are propagated to places of impact. The hazard of earthquakes to people comes largely, but not entirely, through the effect of seismic waves on structures.

The challenge to any SHA is to extract conclusions from large quantities of very diverse data. This section of the report reviews the types of data that must be consolidated, and gives some examples of how these data are combined by means of PSHA to obtain summary statements about the seismic hazard and its uncertainties.

Types of Information

For the predictive statements about earthquakes that may occur within a time span of concern to an engineered facility, prime data come from the following:

- Historical seismicity, over the past few hundred years. Much of the older data are expressed as intensity.
- Instrumental records of seismicity.
- Paleoseismicity, which is the identification of large prehistoric earthquakes by geologic methods. Record of the past 100,000 years is especially significant. Slip rates on faults help in estimating long-term seismic activity.
- Geodetic data. Provide short-term strain rates.
- Tectonic data based on geologic studies. Include long-term strain and slip rates on faults.

Supporting data especially pertinent to identification of seismogenic structures and conditions include:

- Tectonic analysis by deep reflection and refraction seismology and borehole studies.
- In situ stress measurements.
- Potential field studies including gravity and magnetics.

For predicting the strong motion that ultimately affects structures, significant data come from:

- Analysis of observed strong motion recordings.
- Earthquake source-mechanism studies.
- Seismic attenuation studies, both regional and local.
- Analyses of the influence of local ground conditions.

The process of consolidating these data requires, in general, the development of conceptual models to explain the observations, followed by the expression of the models in mathematical form and selection of model parameters. Considerations for seismicity models are discussed here since uncertainty in knowledge of the seismicity is an important factor in all seismic risk analysis. Models for predicting ground-motions are discussed in chapter 6.

The historical record of earthquakes indicates where earthquakes have been generated in modern times, where seismogenic structures and zones are, and thus, where future earthquakes are likely to occur. The record is invaluable, and has been the principal basis for seismic-hazard assessment in the past.

In the western United States, near the continental plate margin, an understanding of the earthquake processes along faults exists, the general pattern of faulting is known, and the historical record provides a usable, though very incomplete, sample of seismicity. There, the seismicity data base compiled with paleoseismic data can provide a degree of credibility to seismic hazard assessments not possible elsewhere.

In the eastern United States, in contrast, the tectonic structures that cause earthquakes are poorly understood. A variety of ideas has been proposed. For example, different tectonic domains above and below subhorizontal, regional detachment surfaces have been suggested, and intrusive bodies at mid-crustal depths may have localized stress and, thus, seismicity. Major preexisting geologic zones of weakness, such as continental rifts or structures defining major crustal density contrasts may also localize earthquakes. Given such unknowns and emerging theories regarding the tectonic associations for earthquakes, seismic-hazard assessments for the eastern United States have been based almost entirely on the seismicity record. Paleoseismological data are beginning to suggest that in regions away from continental plate margins, the so-called "intraplate" tectonic domains, the recurrence time for great earthquakes is measured in many centuries or many millenia. For such regions, the historical record alone is not adequate to assess the true seismic hazard with a high degree of certainty.

Even in the better-understood areas of the continental margin of the western United States, the historical record is too short to have captured even one full cycle or period of recurrence of a great earthquake ($M = \geq 8$). For example, the great earthquake of 1857, which occurred on a segment of the San Andreas fault in central

California, stands alone in the historical record for that segment. Seismic quiescence followed 1857, and continues to this day. If one were to depend only on instrumental data, which began well after 1857, the stretch of the San Andreas fault that generated the 1857 earthquake might be interpreted to be aseismic, whereas paleoseismic data have shown that it has generated great earthquakes at intervals of several hundred years in prehistoric time.

Where seismogenic structures are not obvious, various indirect methods of study can be employed. Gravity and magnetic surveys, seismic reflection and refraction profiling, geodetic networks, and geologic mapping are among the tools and techniques that can be used. Records from regional seismic networks are used to identify which structures are seismogenic. Tentative correlation leading to a theory, followed by testing for verification, are parts of the continuing process of searching for data on which to base rational assessments of seismic hazard.

As valuable and indispensable as existing data sets may be for seismic hazard assessment, each set is incomplete even for the most intensely studied areas, and for many regions almost no significant data exist. New insights and concepts about how Earth mechanisms work have increased greatly in the past decade and are continually emerging at a rapid rate.

Current Practice

The current practices for incorporating earth science information into PSHA varies significantly between the eastern and southwestern United States; therefore, they are discussed separately here.

In the western United States, including Alaska, an effective tool for identifying the seismic sources for a PSHA is geologic data regarding active faults. Faults are mapped at the surface or identified in the subsurface using geophysical techniques, drilling, and trenching. To assess their activity, Quaternary geologic evaluation and geomorphic analyses are conducted to determine the age of most recent displacement. In most cases, faults that have undergone slip in the past 10,000 (Holocene) to 500,000 years (late Quaternary) are considered to be active and are included in the PSHA as potential seismic sources. The candidate faults are also compared with historical and instrumental seismicity data to assess possible associations.

If earthquakes have been observed in the region of interest that cannot be associated with known faults, the source of these earthquakes is usually modeled as a "random" areal seismic source for the PSHA.

Each seismic source must be characterized by its three-dimensional geometry for the PSHA. The location of the surface trace and dip is usually defined by geologic mapping, supported by geophysical data (e.g., seismic reflection) and distributions of earthquake foci. The maximum down-dip extent within the brittle (seismogenic) crust is usually estimated from maximum hypocentral depths in the region. If high-quality instrumental data are available, a focal depth distribution may also be defined for the faults that expresses the relative likelihood of earthquake occurrence at various depths.

An essential characteristic that must be estimated for each fault is its maximum earthquake magnitude. If the fault has been associated with a large historical earthquake, the magnitude of this event may provide a reasonable maximum magnitude estimate. For example, the 1857 and 1906 earthquakes (both about magnitude 8) are often considered maximum events on the San Andreas fault. In the absence of such historical evidence (as is usually the case), maximum magnitudes are usually estimated based on several fault characteristics including total length, rupture length, rupture area, maximum displacement per event, and seismic moment. Each of these characteristics has been empirically correlated with magnitude from observations of historical surface ruptures. The development of data pertinent to estimating these fault characteristics for any given fault has been the subject of rapid advances in the past 5 to 10 years. For example, studies of fault segmentation are allowing estimates of the likely lengths of future surface ruptures. Exploratory trenching and geomorphic mapping are providing estimates of the maximum and average amounts of displacement associated with individual paleoseismic earthquakes. Typically, several methods are used to arrive at several maximum magnitude estimates and these are then combined to form a probabilistic distribution, as discussed later in this section.

A final seismic source characteristic required for PSHA are earthquake recurrence relationships that express the frequency of various magnitude earthquakes up to the maximum. If a fault has been associated with high levels of observed seismicity, then the seismicity data themselves may define the recurrence relationship. More commonly, the observed seismicity includes only small magnitude events and geologic data must be brought to bear to extend the period of observation so that the recurrence of larger earthquakes can be estimated. Geologic investigations along several well-studied faults, such as the San Andreas, have resulted in assessments of recurrence intervals between large events. In most instances, however, the geologic data have served to identify the rate of slip along faults over geologically-recent time periods (past 10,000 to 100,000 years). In fact, recent major geologic studies in the western United States have shown that the fault-slip rate can usually be fairly readily determined. Given that the geometry of a fault is reasonably known, then the slip rate can be expressed as a seismic moment rate over the fault surface. The seismic moment rate reflects the average rate of seismic energy release. It should be noted that this average may remove variations in the recurrence rate that occur over time periods shorter than the period over which the rate is calculated.

To partition the seismic moment rate into earthquakes of various magnitudes up to the maximum, an earthquake recurrence model is required to express the distribution of various magnitude earthquakes. The most commonly used model has been the exponential size distribution model having the form $\log N = a - bM$, where N is the number of earthquakes per unit time equal to or larger than magnitude M, and a

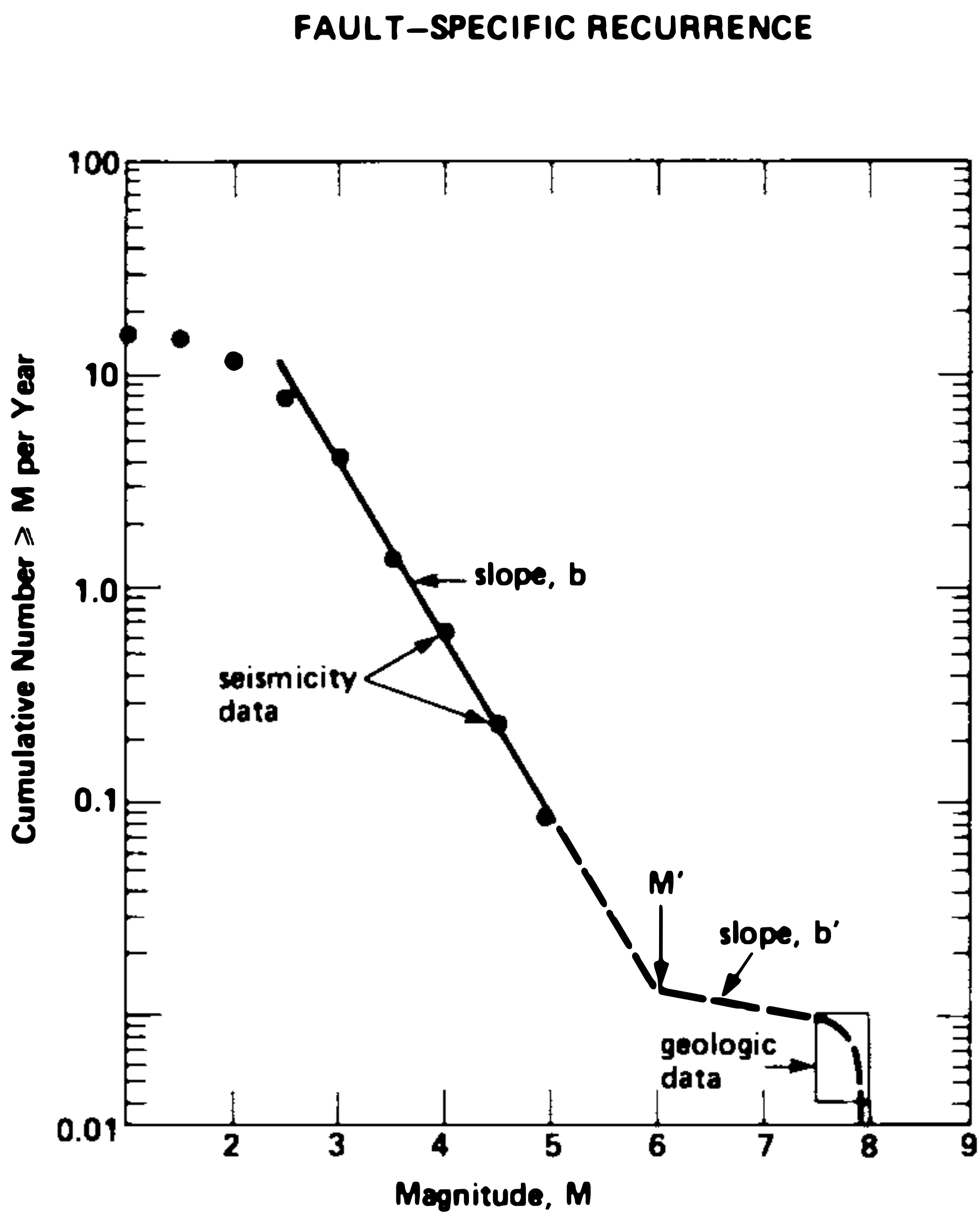

FIGURE 3.4 Diagrammatic cumulative frequency-magnitude recurrence relationship for an individual fault or fault segment. Above magnitude M' a low b value (b') is required to reconcile the small-magnitude recurrence with geologic recurrence, which is represented by the box. (From Schwartz and Coppersmith, 1984.)

and b are constants. Recent geologic studies and seismicity analyses have suggested that although the exponential model appears appropriate for regional seismic sources, a more appropriate recurrence model for individual faults may be that implied by the characteristic earthquake hypothesis (Figure 3.4). Further work is continuing to evaluate the appropriateness of various recurrence models.

In the eastern United States, the uncertainties regarding the association of earthquakes with geologic structure has meant that seismic sources for PSHA are defined largely from observed seismicity. Typically, the seismic sources are areal zones, rather than faults, whose boundaries are estimated from considerations of the spatial pattern of seismicity as well as major tectonic provinces. For example, if a zone of observed seismicity lay along some part of a larger crustal tectonic block such as the Appalachian fold-belt, the entire block might be considered a seismic source for the PSHA. Very recent PSHAs in the east have attempted to further utilize tectonic information by evaluating the probability that known tectonic features (including faults, crustal boundaries, and plutons) might be seismogenic. In areas away from known features, seismic sources in the east are usually defined as large areal zones.

Maximum earthquake magnitudes for eastern sources are typically estimated based on the largest observed earthquakes within the source. If the observed events are not believed to be maximum events, estimates are typically made by assuming that the maximum is an increment larger than that observed (say 1/2 magnitude larger) or by analogy to other seismic sources having similar tectonic characteristics. The lack of fault data in the east has precluded maximum magnitude estimates based on geologic data, up to the present.

Earthquake recurrence relationships for eastern seismic sources are developed from historical and instrumental seismicity data. Because seismic sources in the east are typically areal and are regional in extent, seismicity data are usually sufficient to define a recurrence relationship at least in the low-magnitude range. Extrapolation to larger magnitudes is often necessary and is usually done by assuming an exponential magnitude distribution. It is recognized that uncertainities, which in some cases can be considerable, accompany these types of extrapolation. Paleoseismicity data have been developed for only a few locations (e.g., New Madrid, Charleston) but provide promise for future work.

Treatment of Uncertainties: Examples

Along with efforts to incorporate earth science information into the current applications of PSHA has come the need to account carefully and explicitly for the uncertainties in this information. Summarized here are illustrations of some of the significant uncertainties associated with earth science data in current applications of PSHA and some effective tools being used to document and incorporate the uncertainties into the analysis.

Type IV PSHA explicitly includes uncertainty in all aspects of the analysis, including those aspects pertaining to earth science information. To illustrate current approaches to incorporating these uncertainties, two examples of Type IV analyses are here presented: one for a PSHA conducted for a site in the North Sea within a tectonic environment very similar to the eastern United States, and the other for a site in California.

Figure 3.5 shows a logic tree (see chapter 2 for discussion of logic trees) for characterizing the seismic sources in the North Sea example, and each element of the tree is briefly discussed here. Note that the elements of the tree in Figures 3.5 and 3.6 are examples only; the selection of elements will depend on the site-specific uncertainties of the PSHA. At each node of the logic tree, alternative choices (branches) are given, which capture the range of interpretation. Each branch is associated with a relative weight that is expressed as a subjective probability. Since the logic trees presented here are merely examples, the probabilities shown are for illustrative purposes and are not discussed further.

The first element shows the uncertainty in modeling the seismic sources; two alternatives are to consider the Mesozoic faults of the Viking Graben to be seismic sources or to treat the Graben as an areal source zone. The geologic history of the region shows that some of the faults have experienced greater amounts of slip and more recent slip than other faults, and this might reflect a greater potential for future activation. This is shown in the logic tree as the "1, 3, 5" model of relative activity. Alternatively, the geologic history may not be meaningful to future earthquake potential, as expressed by the "1, 1, 1," model. The focal depth distribution reflects the relative likelihood of earthquake occurrence of various depths. Two alternatives considered are a uniform distribution or one that varies with depth according to the observed focal depth distribution. Large regional "background" source zones have alternative configurations expressed by the area source zone element of the tree.

The b value of the $\log N = a - bM$ recurrence relationship may be defined by considering the b value over the entire North Sea region or by that determined locally within each source zone. Given an earthquake of a certain magnitude, its rupture area can be estimated using empirical or analytical relationships given by either Wyss (1979) or Nuttli (1983). The sense of slip on the faults in the Viking Graben is uncertain and may be either normal or strike slip. Likewise, the dip of these faults is uncertain as shown in the tree. Finally, the uncertainty in the maximum magnitude is expressed as ranging from 6-1/4 to 7, based on the historical seismicity in the region (which is several hundred years long) and comparison with other intraplate regions.

The logic tree for the California PSHA example is given in Figure 3.6. In this case, the elements of the tree can be grouped to show those components that relate to fault activity, source definition (geometry), maximum magnitude, and earthquake recurrence.

The fault characteristics pertaining to the activity of a fault are its recency of slip, associated with seismicity (small or large

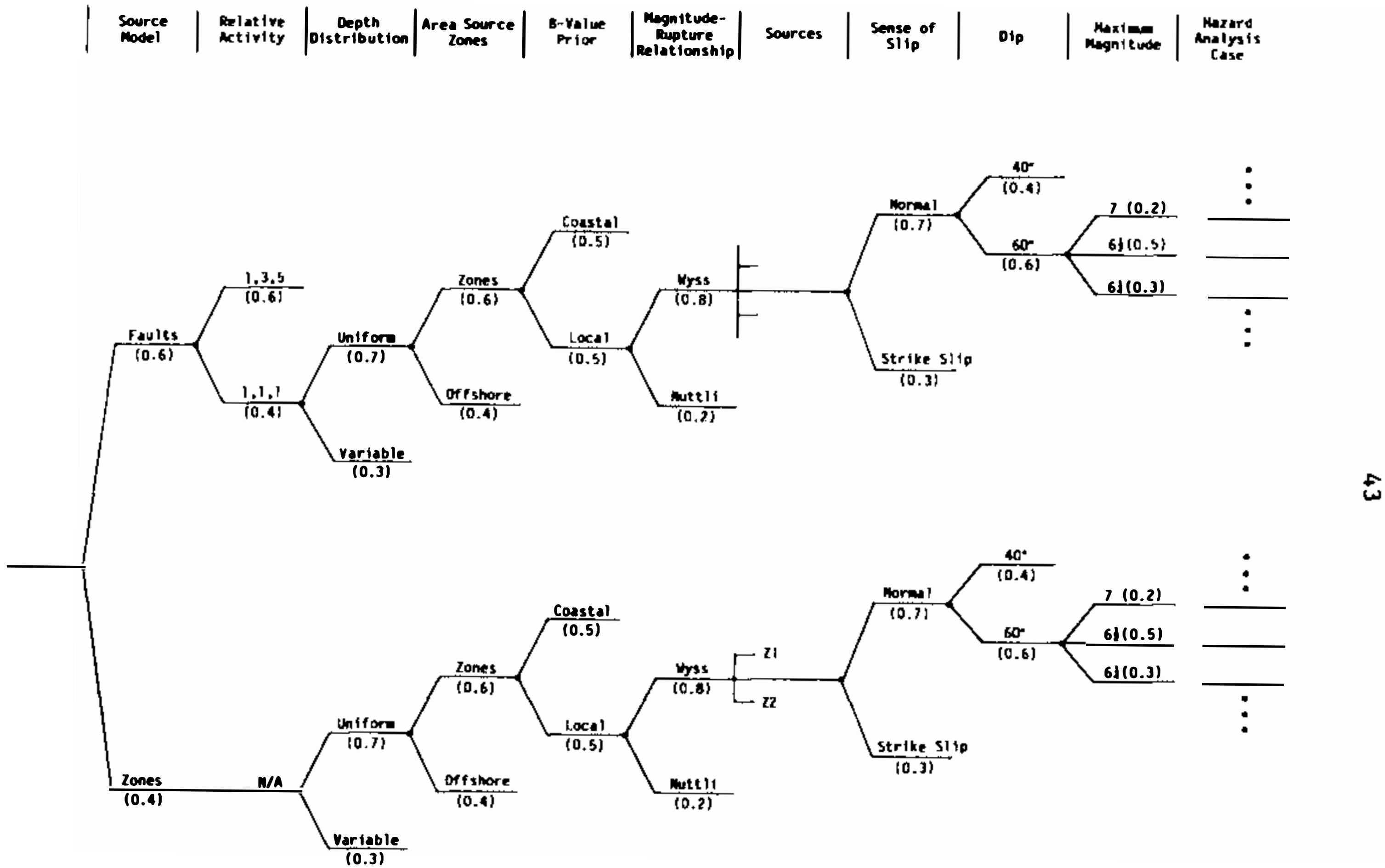

FIGURE 3.5 Example logic tree for seismic sources in the North Sea (After Coppersmith and Youngs, 1986).

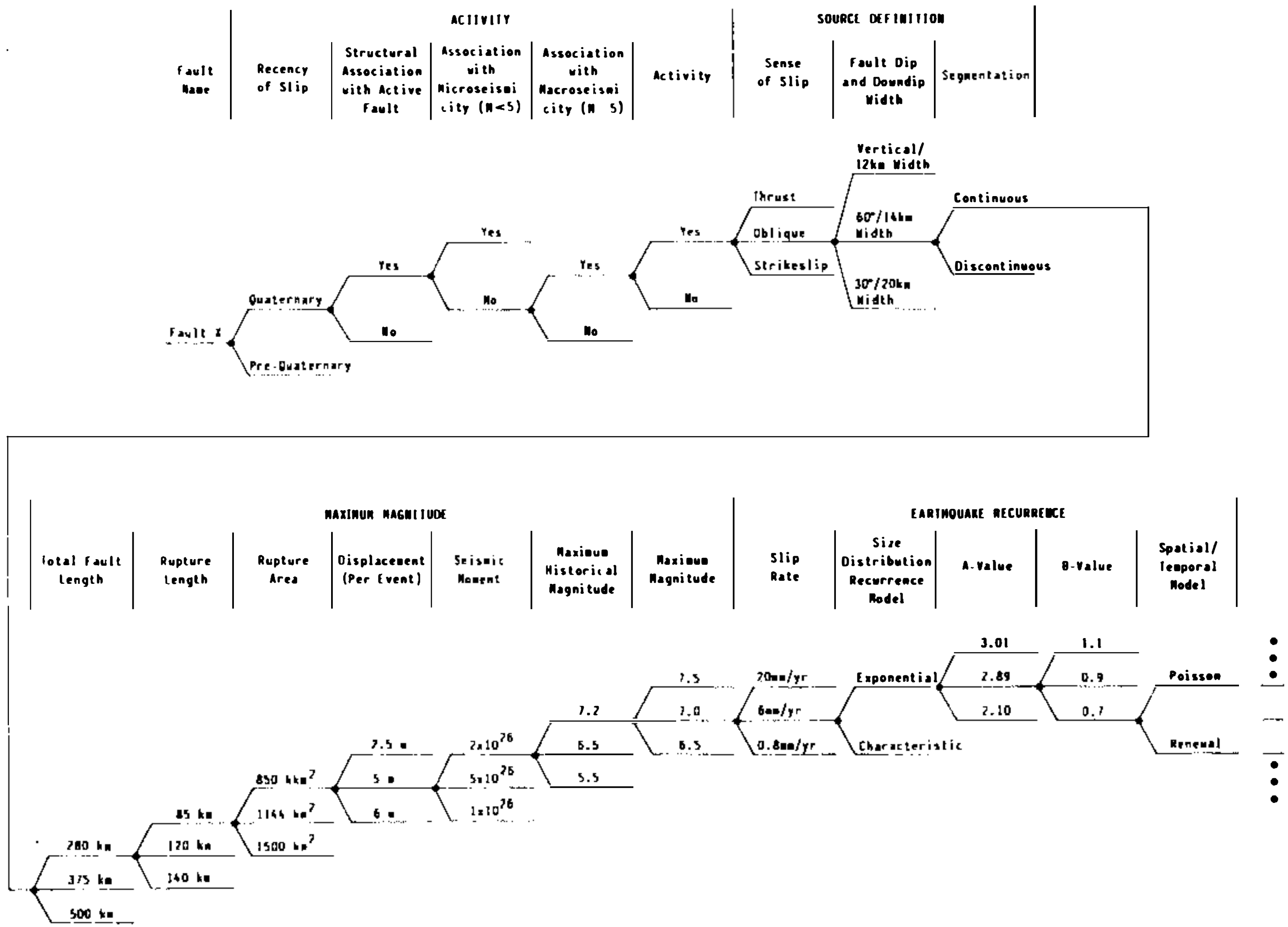

FIGURE 3.6 Example logic tree for fault in western United States (After Coppersmith and Youngs, 1986.).

magnitude earthquakes), and structural association with other active faults. These characteristics in combination result in a probability of activity of the fault.

The fault is defined by its sense of slip, fault dip and down-dip width, and segmentation. Segmentation is an expression of the lateral continuity of the fault along the strike, and it ranges from continuous to highly segmented.

Fault characteristics that are important to maximum magnitude are its total length, rupture length, rupture area, maximum displacement per event, seismic moment (derived from rupture length and average displacement), and maximum historical magnitude. In combination, these characteristics provide a probabilistic distribution of maximum magnitude.

Finally, recurrence related parameters include the slip rate, the recurrence size distribution model, and the a and b values of the $\log N = a - bM$ relationship. The latter (a and b values) may be specified from geologic data or historical seismicity data. A further option is a consideration of the spatial-temporal model of earthquake occurrence, which may contain a memory of time since the last event (renewal model) or be memoryless (Poisson).

Cautions about the use of earth science data are appropriate; new ideas and insights in earth science are rapidly emerging.

The use of expert opinion, especially the use of a panel or panels of experts that can encompass and evaluate unknowns and uncertainties across a broad spectrum of earth sciences, can often provide a means to evaluate and summarize data and interpretations. But experts are fallible, all have limited knowledge and vision, each is subject to some extent to the influences of scientific fads and strong personalities, and not one expert can completely assimilate all currently available data. History is replete with examples where the weight of expert opinions was entirely wrong, and this possibility must be clearly recognized in any seismic hazard assessment.

While we endorse the use of subjective probabilities to quantify uncertainties, an alternative is to express alternative hypotheses (and the resulting hazard curves) without associated degrees of credibility. This course would conform to the classical statistical point of view that probabilities can only represent relative frequencies of occurrence. In our mind, it is more useful for the decision maker to have relative credibilities assigned by the earth scientist and earthquake engineer than to be presented with a set of hazard curves without expression of how credible are the alternatives (in particular, the extreme hazard curves). In short, it is preferable to obtain an expert's assessment of credibilities, because he or she knows the scientific arguments for and against the alternatives. Otherwise a decision maker will make a *de facto* assessment of credibilities when choosing among available alternative results.

Summary

Earth science data, interpretations, and uncertainties, to the extent they are known, can be expressed by PSHA. Standard formats exist and probabilistic methods of dealing with uncertainty are well developed. By its very nature, earth-science information is exceedingly complex, and in the subdisciplines most pertinent to seismic hazard assessment, concepts are changing very rapidly. How can any method summarize and express this state of knowledge and communicate it clearly, concisely, and unambiguously to users when the basic data and interpretations are themselves neither clear nor unambiguous? This is the dilemma.

Very likely no one method of summarizing information, be it mathematical or verbal, can fill the need completely. When information is complex and ambiguous, subjective judgment is required. The value of a mathematical approach, such as PSHA, is that it forces data and interpretations to be quantified as far as possible and requires that the analyst clearly identify which steps are judgmental. To the extent factors are quantified, verification and reproducibility become more feasible, and credibility rises. Credibility, and the confidence it engenders, is a necessary ingredient of the decision-making process.

UNCERTAINTY AND INSTABILITY

It would be ideal if one could predict with accuracy the time and location of future earthquakes, as well as the resulting ground-motions. Decisions regarding earthquake protection would then be both effective and simple to make. For example, one could base decisions on the (known) maximum ground-motion intensity at the site during the next T years, X_t.

Accurate estimation of X_t is, however, not possible at the present time. Consequently, PSHA treats X_t as an uncertain quantity and estimates its probability distribution F, which depends on the current state of knowledge about future earthquakes. Once the distribution F has been calculated, decisions can be based on such distribution.

For example, one might design new facilities for the intensity that is exceeded with probability 0.001 in T years, i.e., for the intensity X such that $F(X) = 0.999$. Implementation of this simple idea is made difficult by two problems: (1) Experts do not necessarily share the same information and often have different beliefs about earthquake occurence, so that their distributions of X_t are different; and (2) Knowledge varies in time, with the implication that the distribution of X_t itself varies in time. This variability of opinion and knowledge results in <u>instability</u>: when more than one PSHA is carried out for the same site, by the same expert at different times or by different experts at a given time, the estimated hazard curves can differ significantly.

The diversity of expert opinion would be of little concern if earthquake decisions had only personal implications for the decision makers, because in that instance each individual could use his or her own distribution F. However, for decisions with societal implications, one must use a more objective definition of F. One usually proceeds in Type IV analysis in the following way: earthquakes are regarded as events generated by a random process R, and F is the probability distribution of X_T resulting from R. Experts are allowed to express their subjective uncertainty on R by considering several possible processes R_i, to which they assign probabilities P_i. The same probabilities are attributed to the resulting distributions F_i.

Displaying subjective uncertainty often helps resolve differences among experts by making explicit the underlying assumptions and data interpretations, and the degree of beliefs assigned to them by each expert. If differences cannot be completely resolved, expert combination procedures can be used to produce a "consensus" set of probabilities P_{i*}. Decisions can then be based on the weighted average (mean) $F^* = \Sigma_i P_i^* F_i$ or on other characteristics of the distribution of F (median, higher fractiles, etc.). If a broad cross section of expert opinions, seismological theories, and analysis methods is included in the study, the final result F^* can be considered representative of state-of-the-art knowledge about future earthquake occurrences; in this sense F^* is an objective measure of earthquake hazard. It should be noted that the process of judgmentally assigning probabilities to hypotheses is not universally accepted as good practice. Indeed, whenever adequate data exist, it is better to regard P_i as the degree to which the data support the i^{th} hypothesis and to calculate it using statistical inference procedures.

Methods of the type just described, with the participation of several experts, are often expensive and are justified only for critical facilities or for making important earthquake mitigation decisions. A simpler way to achieve stability is to impose stronger regulation. Rather than seeking an exact quantification of state-of-the-art uncertainty, one can prescribe the type of process R and the way to estimate its parameters from data, so that the distribution of X_T does not depend on who makes the analysis. Regulatory norms of this type are common in engineering codes, especially for making routine verifications and arriving at preliminary design decisions. This second alternative corresponds to Type III procedure with constraints on the selection of the earthquake recurrence model and on the hazard evaluation procedure.

Because of the large uncertainty that is often associated with earthquake hazard, the evolution of earthquake models and the collection of new data, hazard estimates may change considerably during the lifetime of a facility. If the change is in the direction of higher hazard, the need arises for retrofitting the facility or changing its use, unless these changes have been anticipated as part of an uncertainty analysis. Here again, Type IV analysis proves superior to simpler analyses, because it does not conceal conservatism in the judgmental choice of models and parameters, but forces the decision maker to consider uncertainty and to select the level of conservatism in a rational and quantitative manner.

TESTING AND LIABILITY

Testing

Testing the validity of PSHA involves two distinct aspects: the methodology itself and applications of this methodology. The basic methodology itself is a mathematical procedure, which has been subjected to verification by standard mathematical theory.

Testing the validity of applications of PSHA is difficult. A PSHA predicts the annual probability or rate of occurrence of various ground motions at a site; test of this PSHA therefore includes a determination of whether the occurrence rate of ground-motions is consistent with those predictions. This cannot be done for PSHA estimates of probabilities less than 10^{-2}/year at a specific site, which require hundreds or thousands of years to verify. However, it may be possible to check some of the inputs of the PSHA, such as the ground-motion model, in the near term. Another check is to substitute space for time by looking at the rate of ground motion occurrence over a relatively large region over a time period of tens of years and compare this with the predictions of the rate of occurrence of these ground motions (McGuire and Barnhard, 1981). Of course, this type of comparison cannot check the consistency of local hazard estimates with local sources of seismicity.

In considering the testing of PSHA, it should be emphasized that the testing of the methodology should be separated from the testing of the applications. The PSHA methodology could be sound, yet appli- cations of that methodology could be of poor quality. Thus, it is inappropriate to judge the PSHA methodology solely on the basis of a few applications. It must be appraised in terms of several applications that are conducted consistently with the state of the knowledge in the earth sciences.

Two concepts that may have the appearance of providing a basis for testing PSHA do not provide an adequate test. The first concerns the occurrence of a single major earthquake at a site and the second concerns whether the ultimate consequences of seismic events, such as the loss of life and property damage, are acceptable.

The occurrence of a single earthquake and associated ground-motions in excess of a design level might be construed to represent a failure of a Type I deterministic analysis. However, that occurrence would not define a rate of occurrence that can be compared meaningfully with the PSHA estimates. In the context of an application of PSHA, such events could be rare events that were identified during the hazard analysis but with such low occurrence rate that the design decision was to select a smaller but more probable level of ground motion. Alternatively, they might indicate that the input to the PSHA was not completely adequate.

As stated above, PSHA provides information on possible ground-motion. Further analysis by other disciplines (e.g., structure behavior during seismic shaking, building occupancy) is necessary to relate the output of PSHA to the ultimate consequences. The aim of PSHA is to provide input information to estimate ultimate consequences,not to eliminate those consequences. Thus, the occurrence of, for instance, fatalities caused by seismic events, is not a test of PSHA. Whether society feels that PSHA has failed in such circumstances, or to be more precise, whether society feels that a particular application of PSHA has failed, is a different issue. The testing issue is also different from how society wishes to evaluate risks to potential loss of life and what risks are deemed acceptable.

Although a PSHA relies on the validity of the earth science data and interpretations upon which it is based, it has the potential advantage of capturing the uncertainty in those data and interpretations. It is important to bear in mind that although PSHA can "capture" the uncertainty in some sense, the uncertainties in the understanding of the earthquake hazard still exist. The frequency distributions for the rare seismic events against which seismic resistant designs are intended to resist are poorly known, particularly the largest and most infrequent events. Therefore, following the occurrence of a particular event that might in some sense "test" a design, it is not commonly possible to identify a return period or a probability of exceedance associated with that event, with a high degree of confidence. The earth science profession has much to learn about earthquake hazard, and will continue to learn from the occurrence of most earthquakes with return periods greater than 5 to 10 years.

For example, consider the history of maximum recorded ground-motion parameters. Twenty years ago, when the peak acceleration of 0.5 g was recorded during the 1966 Parkfield earthquake, it was regarded as an outlier. Five years later, the Pacoima Dam accelerogram astounded the seismological/earthquake engineering world with peak accelerations in excess of 1 g and peak ground velocities in excess of 100 cm/sec. Again, these values were regarded by many as special cases, or outliers, for various seismological and engineering reasons. Since then, larger peak ground-motion values have been recorded at the Tabas, Iran (1977), Imperial Valley (1979), and other locations. Now a peak acceleration in excess of 2 g is reported from the December 23, 1985, earthquake in Northwest Territories, Canada. If history is any guide, this value too will be regarded as an outlier until a higher value is recorded in a future earthquake. With the current increased intensity of strong motion observations, this new 1985 value is not likely to hold the record for maximum recorded peak acceleration for 20, or even 10, years.

Numerous recent earthquakes larger than expected for the surrounding area have been recorded. Recent earthquakes that were more extreme than previously expected for their particular geographic area include the 1976 Tangshan, China; 1977 Gazli, USSR; and 1979 El Asnam, Algeria, earthquakes.

What lessons can be drawn from this history? One of the key lessons is reflected in the movement away from the use of peak acceleration as a controlling design parameter. We are currently seeking more "robust" characterizations of ground motion, with a higher degree of engineering significance. But perhaps even more importantly, the lesson is that in designing to resist earthquakes, or even in simply trying to characterize their ground motions, we are dealing with a rich and diverse natural phenomenon. Even with the vastly increased level of strong motion recording, a very limited sample of observations is obtained. Therefore, simple sampling theory shows that although there is now a stable estimate of the distributions of ground motion parameters for some distance and magnitude ranges, the ability to to evaluate risks to potential loss of life and what risks are deemed acceptable.characterize the shape of the distributions is primitive indeed, particularly with regard to extreme values, given the currently available collection of observations.

Of course, the limitations imposed by lack of data and understanding affect all methods of estimating seismic hazard or risk. The only practical means of evaluating or "testing" PSHA, or deterministic seismic hazard analysis (DSHA), in the near term, are the tests of reasonableness and consistency. The designer, owner, and regulator will have the most confidence in a design that can be subjected to various methods of analysis, with consistent results to be obtained that are in accord with the willingness of the owner, and of society, to assume risk. For any current application of PSHA or DSHA, the appropriate test is whether the analysis captures the current state of information of the earth sciences about seismic hazard in a logical, defensible, and useful manner.

Liability

The question of liability for practicing PSHA is fundamentally the same as that arising in any aspect of engineering practice.

> It is the duty of the agent not to be negligent in the performance of his undertaking. Negligence is the failure to exercise that degree of care reasonably to be expected under the circumstances. Breach of this duty makes the agent liable to his principal for the damage caused.
>
> The agent owes to his principal the exercise of that degree of care and skill which a reasonably prudent person would be expected to exercise in similar circumstances. The professional man, the doctor, the lawyer, architect, builder, owes to the person who employs him this duty of care and skill. It is to be observed that, apart from a special contract to that effect, there is no insurance nor warranty that a certain result will be produced; all that the law requires from the holding out is the exercise that of degree of skill, knowledge, and care usually displayed by similar members of the profession in similar circumstances. By accepting an employment whose requirements he knows, the agent impliedly undertakes that he possesses and will exercise that degree of care and skill which a reasonably prudent person would exercise. (Simpson and Dillavou, 1958)

Consequently, the relevant questions involving the liability for the use of PSHA are as follows. Are the techniques consistent with the state of the art and practice, and are the results consistent with codes and standards? The fundamental tests are ones of consistency and reasonableness. For example, are the differences between design values derived from a PSHA analysis and a deterministic analysis explainable, understandable, and reasonable? Taking full account of all the uncertainties, is the level of assumed risk comparable? If PSHA is perceived as a way to reduce costs at the expense of "safety," it may well be regarded as suspect. However, if it is portrayed and perceived as one of a set of tools for estimating an imperfectly known hazard, it should receive the same acceptance as other available methods. A PSHA is one way to arrive at an engineering judgment; it is not a substitute for engineering judgment.

It is interesting to note that an influential court decision used a probabilistic test for "negligence" in a liability case. Judge Learned Hand in United States v. Carroll Towing Co. wrote that "negligence"

> is a function of three variables: (1) the probability that [an accident will occur]; (2) the gravity of the resulting injury--if [an accident does occur]; (3) the burden of adequate precautions. Possibly it serves to bring this notion into relief to state it in algebraic Terms: if the probability be called P;the injury, L; and the burden B; liability depends on whether B is less than L multiplied by P: i.e., whether B < PL. (See G. Schwartz, 1984.)

Thus, although the current state of liability issues in the United States leaves considerable room for uncertainty, there is some legal precedent for just the kind of approach taken by PSHA.

AGGREGATION OF INPUT PARAMETERS

In the calculations for PSHA, ground-motion estimates from many different sized earthquakes at many different distances have been aggregated into a single curve showing ground-motion level versus probability of exceedance. However, in addition to the assurance of completeness and generality, the procedure also has results that are very important to the user community of facility designers and owners, regulators, code writers, decision makers, risk estimators, emergency planners, insurance underwriters, and the general public. These specific results of the procedure are given below as bullets and each is discussed in the context of methods for understanding and clarifying the results of a PSHA.

- PSHA Types III and IV combine very different earthquake energy spectra from smaller near-field events and larger far-field events, at the same maximum ground-motion levels.

For facility designers, regulators, and code writers, this first result is often unsatisfactory. The level and type of facility damage from a 0.5-g ground acceleration resulting from a nearby magnitude 5.0 shock may be vastly different from that caused by a more distant magnitude 7.0 earthquake. This is because of their very different spectral energy contents and duration at the source and at the site. Completely dissimilar ground acceleration time histories, response spectra, and degrees of damage can be expected at a given facility. Disaggregation by use of multiple sets of PSHA estimates to account for different magnitude-distance intervals--e.g., < M 5; M 5 to M 6; M 6 to

M 7; M > 7--each at a range of distances, can be used to advantage here. An effective solution to this problem will require the use of a better way to characterize strong ground motions than the single parameter approach, e.g., by response spectral ordinates at multiple frequencies and for different magnitude-distance-site condition combinations.

• The roles played by specific historical earthquakes are combined.

Facility owners, risk estimators, and decision makers have, in general, been comfortable with a deterministic definition of the design earthquake for certain types of facilities. That is, at least in part, because they could then identify to their constituencies, precisely and succinctly, the level of design safety for their facility. For example, when asked about earthquake hazards they could reply, "Our plant is designed to withstand a reoccurrence of the 1897 magnitude 6.5 shock that occurred in the adjoining county," or, "We have designed against the occurrence of a magnitude 6.0 shock at the plant site and that is 0.5 magnitude greater than the largest historical earthquake within 100 miles of the plant." Such statements are easy to understand and to remember. Additionally, they are based on historical seismicity data that are on record and retrievable by the general public--without calculations. Because the specifics of the seismicity data base are not presented directly by PSHA, such explicit statements on controlling design earthquakes are not possible and must be replaced with more complex equivalents, such as, "We have designed against a level of ground shaking that has only a 1 in 10,000 chance of being exceeded in a given year . . ." Some facility owners and decision makers may be satisfied with such statements, but they are still in a position of being unable to relate directly to known, historical earthquakes that are in the general public memory or knowledge. What would be useful here, in addition to education of the involved parties, is a few sample calculations designed to characterize the PSHA results in layman terms of magnitude and distance. Preferably, however, analyses should be conducted to identify the contributions from various input parameters to the total hazard results. Identification of such contributors could be used, in turn, for additional hybrid combinations of deterministic and probabilistic analyses. The contributors would serve in place of the aforementioned 'few sample calculations.'

• Area normalized seismicity rates (i.e., annual number of events per square kilometer) must be considered.

Whenever areal, i.e., non-point or -line, seismic source areas are employed in the PSHA calculations, the size of that area becomes important because of the markedly nonuniform spatial distribution of seismicity. For example, it is possible to reduce the hazard estimate in the region around a seismogenic fault by assigning the seismic activity on that source to a larger area than it actually occupies. In contrast, the smaller the source area for the same seismicity, the greater will be the resulting hazard estimates. This effect has been referred to as 'spatial smearing' and is addressed by consideration of (source) area normalized seismicity rates.

Area normalization, both regionally and locally, is especially necessary in the eastern United States with its diffuse, buried seismogenic zones. However, it is also important in the western portions of the country where many of the active faults are exposed at the surface, but exhibit marked variability in levels of seismic activity along strike and down-dip. Regional area normalization considerations in PSHA are generally related to achieving an overall compatibility with the historical seismic record, while the local considerations are aimed at preserving concentrations and diffuse distributions in that record and not 'smearing' them without strong geological, geophysical, and/or seismological justifications.

USE OF PSHA BY DECISION MAKERS

A PSHA should be used by decision makers to help make responsible and informed decisions. A PSHA complements other information for considering, evaluating, and communicating the decision-making process and its implications. The specific purposes of SHA should be to create and appraise alternatives, guide data collection and research efforts, and facilitate communication between parties interested in the decision. The ultimate intent is to help make better-informed decisions, resulting in a better balance between the costs of earthquake resistance and the damage and loss of life from seismic events.

It is important to recognize that many of the decision makers involved in crucial seismic problems may not be clearly identified or identifiable at the time the decisions must be made. For decisions about specific projects, designers and investor/owners are clearly recognized decision makers. Other decision makers in the processes may include regulators, members of the legal profession, and interested parties or interveners. On more generic problems concerning seismic hazards, scientists (e.g., geologists, seismologists) and regulators could readily use the information from PSHA in their decision-making processes. For both specific projects and generic decisions (e.g., setting of codes), the processes concerned with important seismic problems occur in technical, legal, financial, regulatory, and political contexts. Quality PSHA should be helpful in any of these contexts. The intent is to provide information helpful in all of them.

With several decision makers, there are clearly several uses of PSHA. One is to assist designers in making better design decisions concerning specific projects. By clarifying the professional judgments utilized in estimating seismic hazards, PSHA can be of considerable help in guiding and designing data collection efforts. This may be of interest to designers, investor/owners, the research community, and regulators. In both of the situations referred to above, the insights may lead to the creation of better design alternatives or better data collection alternatives.

For generic problems of better understanding seismic hazards, the processes by which they occur, and the regulations, which should control specific projects with respect to seismic hazard, PSHA can also help in suggesting and evaluating alternatives.

Two key roles of PSHA are relevant to all potential decision makers. The first is to represent and communicate logically the information that was used in the PSHA. In this regard, it is particularly important to report fully the information and insights generated from the various components of a PSHA, rather than to report only the aggregated calculated impacts for ground motion at a site. This allows one to appraise the quality of different information and its relevance to the results of the PSHA. Closely related to this is the fact that a PSHA documents the processes for appraisal. In short, PSHA allows interested parties to examine better both the results of the analysis and the decision making process.

It is important to recognize that many of the potential benefits of a PSHA result from the inclusion of the results of a PSHA in a more general decision analysis (see Keeney and Raiffa, 1976, or Keeney, 1980). Fortunately, PSHA is completely consistent with the general use of quantitative risk analysis and decision analysis in science, technology, and public policy.

The intent of PSHA is directly in line with the intent of quantitative risk analysis and decision analysis. It is to provide a framework for communication and evaluation given the multidisciplinary nature of the problem, its complex relationships, and inherent uncertainties. The focus of PSHA and other risk analyses is different. Specifically, PSHA never addresses the fundamental consequences of interest in the problem, namely those consequences pertaining to the physical damage and loss of life and injury that may result with the occurrence of a seismic event. The output of PSHA pertains to the levels of ground motion, which are only of interest in that they are means to these more fundamental consequences. This distinction becomes important in how PSHA should be used by various decision makers.

The methodology of PSHA is completely consistent with the methodology of quantitative risk analysis. In both, probability is used to quantify uncertainty; models, data, and expert judgment are utilized to select and use the models; and the outputs of interest are reported probabilistically. Clearly, the specifics of seismic hazard analysis are often different from those in risk analysis simply because different disciplines are involved. Analyzing the risk of air pollutants requires knowledge from meteorology and physiological effects of pollutants, and these are clearly distinct from the analysis of the occurrence of earthquakes and the transmission of energy through the earth's surface. The application and use of PSHA and decision analysis must be distinct, as the decision makers concerned with seismic events will not necessarily be able to interpret the implications of ground motion. In decision analysis, if the implications of the alternative are analyzed further to indicate their relevance to fundamental consequences, such as property damage and loss of life, the "real decision makers" can directly gain insights from the analysis.

To elaborate, the results of PSHA indicate probabilities of specified levels of ground motion being exceeded at a given site. Most of the decision makers concerned about seismic hazards will not be able to interpret the significance of those various levels of ground motion. Only individuals with training involving the interaction of structures and ground motion will be able to interpret such information directly. These technical experts must either interpret the implications of the information for all other decision makers, or additional analysis that relates that information to the specific concerns of the other decision makers is necessary. For example, the other decision makers would be directly interested in the safety and economic implications of various designs for a facility at a given site, rather than in the ground motion, as such, at that site.

A PSHA alone does not and cannot indicate whether the consequence of the hazard is what might be referred to as an acceptable risk. A decision about whether or not any risk (or any alternative action) is acceptable or desirable depends on (1) what the seismic hazard is at a site, (2) what the consequences (e.g., fatalities, economic costs) of that hazard may be, and (3) the acceptability or desirability of these consequences. Item 1 refers to the information provided by a PSHA. Item 2 refers to information provided by disciplines other than those trained to estimate seismic hazards. Both items 1 and 2 refer to factual information, although there may be differences of opinion and uncertainty about these facts. Item 3 must be based on value judgments supplied, implicitly or explicitly, by the decision maker(s). If additional clear thought, supported or not supported by additional analysis, is not included to address items 2 and 3, both the power and the responsibility for decision making falls on a few people with technical training. This places a much greater burden on technical experts by requiring them to make value judgments that are neither their responsibility nor within their area of expertise.

To illustrate the dilemma faced by decision makers when only a PSHA is provided (without items 2 and 3), consider the typical actions required when a Type IV PSHA result is presented. When faced with a seismic hazard curve that is accompanied by a wide range of uncertainty, the decision maker will likely focus on a single, usually central, estimate of hazard. Unfortunately, alternative estimates such as the mean, the median, and the 0.9 fractile have, in most instances, very different decision implications. Faced with the problem of selecting just one estimate, decision makers have typically pursued one of the following options.

1. Pick the estimate based on judgment or on current practice.
2. Envelop the uncertainty range displayed and see whether one can live with the concurrent decision. This approach often appears with highly contested critical facilities.
3. Disregard the PSHA and indicate that its results should be used for insight alone. A search is then made for a deterministic "silver bullet", which would appear to obviate the need for probabilistic analysis.

Each of these approaches to some extent abandons, limits, or misuses the wealth of information obtained in a Type IV PSHA. Surprisingly little has been done to help make the most effective use of PSHA. The assumption is often made that the scientist/engineer finishes his or her job when the analysis is completed. While this may be true in the abstract, in reality, the results of the analysis are often so complex and laced with proper caveats that the needed information is almost impossible to understand. This situation can and should be remedied by informative interaction between the scientist/engineer and the user/decision maker so as to organize the information being transmitted in a manner most suitable to solving the problem at hand. In general, formal techniques and insights gained from decision analysis have yet to be applied in any meaningful manner to the use of PSHA. Without increased attention to the problem of decision making in the face of uncertainty, in many instances, PSHA may not go beyond being a powerful but underused tool.

All decision makers should definitely understand that PSHA does not make decisions. It can and should only help decision makers make decisions by providing insightful information. Hence, it should be clear that PSHA is only a complement to everything else in the decision-making process. The choice is not whether to perform PSHA or something else, but rather, in any specific context, whether the addition of a PSHA offers benefits commensurate with the effort required.

4

WHAT CONSTITUTES AN ADEQUATE PSHA?

The adequacy of PSHA depends on the appropriateness of the type chosen for a given application and on the way in which the analysis is conducted.

As a general rule, sophisticated, Type IV methods, which aim at accurately quantifying uncertainty on future earthquake loads, are appropriate to make decisions concerning either single critical facilities or large classes of ordinary structures. Type III analyses, possibly regulated as was mentioned earlier in chapter 3, are adequate for the analysis and design of important but less critical facilities. For certain applications, such as earthquake loss estimation and earthquake relief planning, a semiprobabilistic approach may be more convenient. In this instance, one or more "design earthquakes" are specified based on a probabilistic model of earthquake occurrences. These design earthquakes are then used to evaluate losses and to compare alternative preparedness and relief plans. The reason a semiprobabilistic approach is adequate is that consideration of all possible earthquake scenarios would be excessively expensive and the results of a complete probabilistic analysis would be less easy to interpret by the intended users.

The other aspect of the adequacy issue refers to the way the analysis is made. The general requirement is that the analysis be consistent with the current practice of earthquake hazard estimation. This applies to the formulation of physical theories, to the probabilistic modeling of earthquake occurrences, to statistical data analysis, and to the elicitation and use of expert opinion, if such elements are part of the analysis. More specific steps to ensure the adequacy of a given PSHA are as follows.

1. There should be documentation of the modeling assumptions and parameter-selection procedures used in the analysis. This should include consideration of geologic, tectonic, and historical seismicity information.

2. Historical earthquake data may be used to verify the plausibility of hypotheses by comparing the predicted earthquake recurrences with those observed from historical seismicity. This check may lead to discarding as inappropriate, or to downweighting as unlikely, hypotheses, models, or expert opinions that would otherwise be influential on the final results.

3. Type IV and Type V analyses aim at quantifying professional uncertainty on earthquake hazard. Other PSHA methods, e.g., Type III analyses, do not. It is however desirable that, through sensitivity analysis, statements of uncertainty be made, so that a false sense of accuracy is not conveyed when results are based on just one hypothesis.

4. For certain applications, it is important to identify the combinations of magnitude and distance that contribute the most to earthquake hazard. For this purpose, one should calculate the joint probability distribution of magnitude and distance for earthquakes that produce site ground motions equal to or larger than any given value.

5

RECOMMENDATIONS FOR IMMEDIATE APPLICATIONS OF PSHA

The opportunities for the near-term application of PSHA are a function of several factors including the probability level of interest, the degree of uncertainty regarding the seismic environment, and the type of structure under consideration. All of these factors are interrelated but for purposes of outlining recommendations for application of PSHA, they are treated here separately. In discussing below the applicability of hazard assessment methodologies, a spectrum of approaches is considered ranging from deterministic methods (Type I) to simple probabilistic methods (Types II and III) to sophisticated probabilistic methods (Types IV and V). Recommendations for application of PSHA are given below as a function of the probability level of interest, the degree of uncertainty, the motivation for conducting the hazard analysis, and the interrelated application of the results of the study.

PROBABILITY LEVEL OF INTEREST

The probability level of interest for a particular PSHA is usually closely tied to the type of structure or engineering application. Recall that this is the probability of exceeding a level of ground motion, not of causing failure of the structure. Higher probability levels (10^{-2} to perhaps as low as 10^{-3} per year) are usually appropriate for residential or commercial low-rise buildings; moderate probability levels (10^{-2} to 10^{-3}) for larger, more expensive commercial structures, such as high-rise buildings and offshore oil production platforms; and lower probability levels (10^{-3} to 10^{-7}) for critical facilities, such as nuclear power plants as well as long-lived structures, such as dams and nuclear waste repositories. These annual probability levels do not reflect probabilities of failure, as there is usually significant conservatism in the design of the facility for ground motions with these probability levels. For example, the seismic resistance of a single-family woodframe house to collapse can be considerable. Rather, these probabilities indicate how rare the event should be that the facility is designed to withstand.

At higher probability levels, building design is usually based on building codes and their associated provisions for seismic resistance.

Typically, PSHA is not considered necessary to assess the design levels for these types of structures except to check the probability levels implied by the building code.

Moderate probability levels are usually considered appropriate for larger commercial facilities. The moderate probability levels of interest (10^{-2} to 10^{-3} per year) are usually higher than the annual frequency of occurrence of the largest earthquakes. This is especially true in low activity environments, such as the eastern United States, where the frequency of large earthquake occurrence may be 10^{-3} to 10^{-4} per year on an individual seismic source. Therefore, the use of a deterministic approach, which assumes the occurrence of the maximum magnitude earthquake, may imply very low probability levels.

Probability levels of 10^{-2} to 10^{-3} per year may require an extrapolation beyond the historical data in eastern North America, and even though these levels can often be constrained by geological data in the western United States, the uncertainties on PSHA at these levels are large enough to have a significant impact on building designs (e.g., see Figure 2.5, p. 19). Without prescription (see chapter 3) or other measure being taken to reduce instability, the application of single model PSHA (Type III) to set design levels for engineered structures could result in considerable variability in design levels among different studies. If suitable techniques are adopted to reduce or eliminate the variability, single model PSHA is an acceptable method for establishing seismic resistance criteria in these cases.

Low probability levels (< 10^{-3} per year) are usually appropriate to critical facilities (e.g., nuclear power plants, LNG facilities), very expensive commercial facilities (large oil production platforms), and long-lived engineering structures (major dams and nuclear waste repositories). In more active seismic environments, such as along the more active faults in the western United States, the recurrence rate of the largest earthquakes on individual faults is about 10^{-2} to 10^{-4} per year. Thus, in these environments, the results of PSHA at 10^{-3} probability levels and the results of deterministic hazard studies may tend to provide similar estimates. However, this may not be true where, for example, sites lie close to active faults and smaller, more frequent earthquakes contribute most to the PSHA result. In lower activity environments, such as the eastern United States, ground-motion results from PSHA and deterministic methods may be very different, even at low probability levels, because of the lower recurrence rates in these regions. At low probability levels, both deterministic (Type I) and probabilistic hazard studies should be conducted to arrive at appropriate seismic design or evaluation criteria. The PSHA should be sophisticated (Types IV and V) to include the uncertainties associated with low probability levels and to account adequately for the characteristics of the earthquake setting. The results of the PSHA should be disaggregated to determine the sources, magnitude, and distances of earthquakes that are dominating the hazard (see chapter 3). The probabilistic result can provide a quantitative basis for assessing the reasonableness implied by the deterministic estimate.

DEGREE OF UNCERTAINTY

At present the uncertainty regarding the seismic hazard at particular locations in the United States is highly variable. To a large extent, this stems from variability in the knowledge of the sources and rates of seismic activity. In general, the level of uncertainty at locations in the United States is related to the rate of seismic activity. For example, in much of the eastern United States, causative geologic structures are largely unknown; therefore, the use of tectonic data to constrain the location and rate of seismicity is limited. At some locations in the western United States, the relation of stresses to plate tectonic mechanisms and causative faults is more readily recognized, although the frequency of earthquake occurrence may be difficult to estimate. As the level and sources of uncertainty are variable from site to site, it is highly desirable to capture and properly display the uncertainties associated with the characteristics that are most important to hazard assessments at any particular location.

At some locations, the degree of uncertainty will be very high. Earthquake causes, mechanisms, and locations may be poorly understood. An inadequate historical seismicity record may preclude confident estimates of earthquake recurrence or even the likely location of seismic sources. Geologic data regarding prehistoric earthquake activity may be totally unavailable. (This level of uncertainty characterizes large parts of the mid-continent region of the United States.) In these instances, it is difficult but necessary to define the range of uncertainty in earthquake source characteristics required for a PSHA based on existing knowledge.

In some instances, the level of uncertainty may be very low. The geometry of the causative fault may be known, the historical seismicity and geologic data may provide strong constraints on earthquake recurrence, and the earthquake recurrence behavior may be well defined (e.g., time-predictable behavior). The seismic source in this instance would likely be a very active fault. Because the range of uncertainty regarding source characteristics would be low, the PSHA would tend to simplify to those "preferred" estimates based on the data (i.e., the analysis would become increasingly deterministic). The rate of activity on the source would likely be very high to allow such a confident characterization; therefore, the results of the PSHA would likely be very similar to results from a deterministic analysis (i.e., the maximum earthquake would occur frequently enough to be important to the PSHA).

At present, the instance of very high uncertainty described above is rather common in the United States, particularly in the central and eastern United States. The probability level associated with a particular ground-motion level may vary by over two orders of magnitude. The opposite situation, of very low uncertainty, however, is extremely rare. Even the well-studied segments of the San Andreas fault have not experienced sufficient historical seismicity to validate recurrence estimates based on geologic data. Perhaps the highly active faults in China, coupled with the long historical record, offer the best hope of verifying models of earthquake behavior.

Commonly, we are faced with moderate levels of uncertainty regarding the seismic hazard at a site (i.e., the uncertainties and probability level from the 15th to 85th fractile, represents about one to two orders of magnitude; see Figure 3.3). Seismic sources can typically be identified by active faults, tectonic features, or temporally stable zones of seismicity. Either a fairly long historical seismicity record (e.g., northeastern United States) or geologic strain rate data (western United States) are available to constrain a range of recurrence estimates. The available tools of PSHA provide a suitable basis for capturing this level of uncertainty without misrepresenting the actual level of knowledge (i.e., the statement of uncertainty can be made very explicit). It is therefore recommended that where moderate to high levels of uncertainty exist, sophisticated PSHA approaches be employed to properly incorporate and display these uncertainties.

MOTIVATION FOR CONDUCTING HAZARD ANALYSIS

The motivations for conducting a PSHA may be quite varied and can have an impact on the applicability of PSHA or deterministic approaches. In general, we can divide the motivations into economic incentives and safety incentives. Obviously, these motivations are not mutually exclusive and both may be equally important to deciding whether to conduct a PSHA for any given engineering application.

A consideration of economic incentives for conducting a PSHA involves a balance between the initial cost of the engineered structure plus the cost of remedial measures in the event of seismic damage versus the probability of occurrence of various levels of earthquake damage. Consider two extremes: (1) a low-rise commercial office building that is built to code and has a design lifetime of 50 years; and (2) a 375-m oil production platform in the North Sea costing $3 billion and having a design lifetime of 30 years. Note that in this example, the number of individuals who might be directly affected by the seismic safety of the platform is limited to a few hundred people. The economic consequences of seismic damage, however, are quite different and are usually weighed against the cost of designing for earthquakes of various levels. In the instance of the office building, seismic provisions of the building code typically provide a basis for design. Simple PSHA analyses are sometimes made to assess the degree of conservatism represented by the code requirements. In the instance of the offshore platform, the economic consequences of failure usually demand that the design be sufficient to avoid collapse for rare events. This is true even in low activity intraplate tectonic environments such as the North Sea. For these types of expensive structures, the probabilistic treatment of risk (cost) owing to nonseismic events such as wind and wave loading is common practice. Therefore, sophisticated PSHA is readily accepted and amenable to conventional cost/benefit analysis. Thus, the appropriateness of PSHA and the level of PSHA may vary as a function of the economic consequences of seismic damage or failure.

A major motivation for seismic hazard analysis is public health and safety. In the United States, the design and evaluation of critical facilities, such as nuclear power plants and dams is government regulated. Quantitative safety goals (expressed as risk per year) are being considered by the Nuclear Regulatory Commission, but have not been implemented. The desire for conservative design of critical facilities has led to the implementation of deterministic approaches to establishing seismic design levels. In practice, these approaches are based on "worst case" scenarios whereby the largest credible earthquake is assumed to occur at the closest approach of the seismic source to the facility site.

At present, acceptable levels of probabilistic seismic hazard analysis (i.e., annual ground-motion exceedance rate) have not been established for the design of critical facilities in the United States, although other countries, such as Canada, have done so. In the United States, a PSHA typically provides a basis for evaluating the design bases of existing facilities. For example, PSHA is being considered for application to nuclear power plants by assessing the exceedance rates of the design bases at existing plants. Until quantitative safety goals are established, PSHA is likely to be used increasingly to evaluate the relative adequacy of seismic design bases arrived at by using deterministic approaches. These PSHA studies should be sophisticated (Types IV and V) to capture effectively and display the full range of uncertainty in the hazard analysis such that the previous design values can be evaluated fully. The appropriateness of regulatory specification of acceptable levels of hazard or risk expressed in probabilistic terms should be further examined for implementation in the United States. In the future, PSHA should play a major role in establishing design bases for engineered facilities.

INTENDED APPLICATION

Seismic hazard analyses are conducted for a variety of purposes ranging from site-specific engineering design to regional land use planning. The applicability of PSHA vis-a-vis deterministic approaches, and the type of PSHA conducted also appear to vary with the purpose intended. Three typical applications are considered here: regional studies, site-specific studies, and subregional siting studies.

Regional PSHA studies are usually developed to provide a geographical portrayal of the spatial variation of hazard levels on the scale of a state. Ground-motion values are typically contoured and given for probability levels of about 10^{-2} to 10^{-4}. Examples are the maps prepared by the United States Geological Survey (USGS) (Algermissen et al., 1982). These studies are intended to provide a basis for regional planning, but are not intended for site-specific use. They are usually simple PSHA (Type III) based on generalized seismic sources and do not attempt to incorporate or display uncertainty in the analyses.

Site-specific PSHA studies are usually conducted to provide seismic design criteria for engineering structures or to evaluate the design of existing structures at a single geographical location. Studies have shown that site-specific PSHA can be very sensitive to details of the seismic source characteristics, such as the proximity of sources to the site and earthquake recurrence rates, as well as to site engineering properties, such as soil conditions. To specify the particular seismic environment unique to a particular site, sophisticated PSHA (Types IV and V) are usually required.

Increasingly, hazard analyses are being conducted over relatively small regions (tens of kilometers) for the purpose of siting engineering facilities. An example might be a PSHA conducted within an offshore lease block (say 30 km^2) with the purpose of determining the relative levels of hazard within the block to aid in siting an oil production platform. Another example might be hazard studies along a 200-km coastal strip to assess the relative hazard levels that might affect potential sites for a proposed major dry-dock facility. To characterize effectively the spatial variation in hazard levels, a grid of site-specific hazard is typically carried out. The density of the grid is a function of the scale of variation in the seismic sources, and a detailed PSHA must be conducted to characterize properly the seismic sources and site conditions. Although the multiple PSHA calculations required for the grid can be extensive, modern computation capabilities have greatly reduced the cost.

SUMMARY

A consideration of the present and potential usages of PSHA allows us to arrive at the following conclusions and recommendations regarding the immediate applications of PSHA.

1. Simple PSHA approaches (Type III), which do not involve detailed uncertainty treatment and with provisions to reduce or eliminate variability, are appropriate where the probability levels of interest are moderate ($> 10^{-3}$ per year), as for commercial buildings; the analysis is being conducted for noncritical facilities (i.e., noncritical to public health and safety); economic incentives justify evaluating the adequacy of conventional design based on existing building codes; or a regional PSHA study intended for planning purposes is being conducted.

2. Sophisticated PSHA studies (Types IV and V) that fully characterize seismic sources and incorporate uncertainties are appropriate where the probability levels of interest are relatively low (10^{-3} to 10^{-6} per year), such as for critical facilities; economic and safety incentives require consideration of "rare" seismic events; or the hazard analysis is being conducted for site-specific or subregional engineering purposes, such that the unique seismic environment must be fully characterized.

3. In many instances, the design of existing engineering facilities has been carried out on the basis of a deterministic characterization of the seismic hazard levels. This is true for the dams and nuclear power plants in the United States. It is recommended that, where reevaluation of these facilities is required, PSHA can be particularly effective for investigating the relative levels of conservatism of the design bases for these facilities. The PSHA can also be used in this way to consider improved knowledge of the tectonic environment and to display effectively the uncertainties in the hazard results.

6

FUTURE DIRECTIONS FOR PSHA

Future directions in probabilistic seismic hazard analysis (PSHA) will be guided by developments in the underlying earth science disciplines and by further refinements in the PSHA methodology itself.

This chapter is divided into three sections focusing on better information that is needed for the description of the distribution and occurrence rates of earthquakes, on an improved description of the ground motions during earthquakes, and on needs for the methodology of PSHA itself.

TECTONIC MODELS

Physical Understanding of Seismicity

The first type of information needed for PSHA is a specification of the earthquake locations, sizes, and frequency of occurrence. The principle source of such data to date has been the catalogs of past earthquakes, which have been developed from historical sources and from seismographic networks. It should be noted that the quality of information from historical sources, such as newspaper descriptions of earthquake effects, is in no way comparable to the quality of information obtained from instrumental networks. Immense efforts have been dedicated to the careful analysis of historical data, to estimate the probable level of completeness of catalogs and the sizes and probable locations of the events that are included. To visualize the difficulty associated with that task, one need only consider how inadequately the seismicity of California could be reconstructed from newspaper coverage during the 1980s. These observations emphasize that the information in the catalogs from the modern seismographic networks, which can only be gathered in real time, is extremely important for present and future generations of hazard estimation.

The basic reason for analysis of the preinstrumental catalogs of earthquakes is that instrumental catalogs do not reach far enough into the past. The repeat times of earthquakes on most faults are long, compared to the years covered by the instrumental seismicity catalogs. Therefore, to reduce uncertainties in the PSHA estimates, it is essential to study the preinstrumental historical events and prehistorical events determined from geological studies. These same considerations also demonstrate that it is essential to continue to maintain high-quality instrumental networks for earthquake location and tectonic interpretation for the indefinite future. Regional networks for basic observation and portable seismographic recorders for detailed studies of aftershock sequences both provide important and complementary data.

Geological Studies

Geological techniques are important in identifying seismogenic structures and in estimating the sizes and frequencies of occurrence of the larger events, which are likely to occur on each structure that is identified. For example, the primary basis for identifying seismic sources in locations of the western United States are geologic fault studies. Geological techniques are expected to improve the understanding of seismicity in several ways.

First, geological and geophysical studies can contribute to the understanding of the causes and the rates of occurrence of earthquakes in all regions of the country. In California, within the framework of plate tectonics, plate interactions are the clearly identified causes for many of the earthquakes. In the Pacific Northwest, there have not been any great earthquakes in historical times, but based on plate tectonics, large earthquakes might be expected. Geological studies may provide evidence of large seismic events in the prehistoric record or they may verify the absence of these events over geologic time. East of the Rocky Mountains, however, the geological processes giving rise to earthquake faulting and the rate controlling mechanism for these processes have not been identified. Some candidate processes include ridge push, post-glacial rebound, loading the crust with sediments in the Mississippi Delta and related arching of the crust nearby, and subsidence in the Michigan Basin; but the relationship of these to earthquakes has not been established.

Within the context of an overall understanding of the tectonic processes and their rates, there is a need to identify regional structures that cause earthquakes, and to determine their rate of deformation and the sizes and frequencies of earthquakes that accompany the deformation. Recent studies of the paleoseismology along active fault zones in the western continental borderland and Basin-Range province have served to establish relative degrees of activity among various faults. It is now generally accepted that faults differ widely; their earthquake potential is expressed as maximum earthquake magnitude, slip rate, and recurrence intervals. For example, paleoseismic investigations involving exploratory trenching, Quaternary mapping, and geomorphic analysis have shown that the recurrence intervals between large earthquakes varies from hundreds of years to several tens of thousands of years on faults in the western United States and within similar tectonic environments worldwide. The geologic methods and investigative tools for arriving at these conclusions have evolved rapidly in the past decade and should continue to evolve rapidly in the future.

For a fault that has been identified, the ideal input for a seismic hazard study includes the location of rupture, distribution of sizes, and corresponding occurrence rates of earthquakes on the fault. Additional research is needed to improve our understanding of the relationship of these dynamic earthquake processes and the observable relationships preserved in the geological record.

Examples of emerging concepts in these areas that hold promise for the future are fault segmentation, characteristic earthquakes, and geologic seismic moment rate. Observations of surface faulting during historical earthquakes have shown that faults typically do not rupture their entire length, but rather by segments. By using these historical observations as a guide to define the geologic conditions at the ends of rupture segments, geologists are examining fault zones for evidence of segmentation associated with prehistoric ruptures. If these segments can be identified along faults that have not experienced historical rupture, the possible location and size of future events might be estimated. Detailed paleoseismic investigations along faults such as the Wasatch and San Andreas have provided evidence of the size of the prehistoric earthquakes (from the amount of displacement and extent of rupture). These studies suggest that individual faults and fault segments tend to generate a "characteristic earthquake" of about the same size repeatedly. The information from this model of earthquake occurrence is being compared to historical seismicity data to determine appropriate recurrence models to use in a PSHA. Slip rates are a powerful tool for characterizing the recurrence of faults from geologic data. By determining a geologically-recent slip rate and a reasonable fault geometry, a seismic moment rate can be derived that can be expressed as the frequency of various magnitude earthquakes. This moment rate can also be compared on a local or regional basis to moment rates derived from historical seismicity data.

Various types of nonfault surface deformations, such as folding, uplift, and subsidence, may provide clues about the geological processes that are occurring below. For example, during the magnitude 6.5 Coalinga earthquake (1983) no surface faulting occurred, but the surface fissured as the ground bent upward to form an anticline. Inferences about the existence and character of the buried faults from surface observations was difficult and should be the subject of future studies. The geologic evidence, however, provides clear indications that previous episodes of surface faulting have occurred in the geologically-recent past.

At various locations in the central and eastern United States, paleoseismic studies have identified effects of past earthquakes. For example, paleoliquefaction and deformation of young sediments has been documented at Charleston, South Carolina, and near New Madrid, Missouri. The recognition of geologic evidence for recent faulting on the Meers Fault in Oklahoma has been significant. These are examples of the kind of research that have the potential to define better the seismic hazard and should be coupled with ongoing studies to understand the fundamental tectonics of the cause of earthquakes in the eastern United States.

In summary, research is needed on a number of geological techniques related to active tectonics. The specific techniques that are needed include improved dating of Quaternary material (less than 2 million years), tectonic geomorphology (understanding rates, styles, and patterns of surface changes), geodesy (measurement of deformation of the earth surface), and paleoseismology (including physical exploration and geomorphic analyses in critical locations of the geological effects of past earthquakes). Physical models are needed to express the results in a form most useful to PSHA. A recent report (National Research Council, 1986) has reviewed these fields in more detail.

Intraplate Seismicity

Because considerable uncertainty exists regarding the causal mechanisms and likely locations of significant earthquakes in the eastern United States, future research should focus on several key areas. Recent studies of the state of crustal stress in the East have shown that the state of contemporary stress is almost uniformly compressional. Continued study of earthquake focal mechanisms, in-situ stress measurements, bore-hole breakout data, and geologic indicators will provide insight into the orientation of stress. These data, as well as tectonic considerations will lead to a better understanding of the tectonic mechanisms for these stresses and, in turn, may provide clues to the location and rates of seismicity.

To help understand the reasons for the probable locations of earthquakes in the East, careful studies are being carried out for a better understanding of the tectonic structures that are present at the locations of known zones of seismicity. Some examples are New Madrid, Missouri; Charleston, South Carolina; La Malbaie, Canada; and the central Virginia seismic zone. Included in the studies are evaluations of instrumental seismicity to establish spatial correlations with tectonic features. High resolution network monitoring is invaluable in this respect and continued study in this area is highly recommended.

To help understand the causal mechanisms and maximum size of earthquakes associated with seismic sources in the East, studies should be encouraged of historical earthquakes within the intraplate environments worldwide. Looking globally at the association of large earthquakes with known tectonic characteristics, stress state, and history of seismicity holds promise for better understanding of these factors as they pertain to the eastern U.S. earthquakes.

Statistical Earthquake-Occurrence Models

Several earthquake-occurrence models have been proposed, showing various degrees of sophistication and incorporating different physical concepts. Anyone may consider a variety of probabilistic dependencies and memory patterns involving earthquake times, locations, and sizes. Examples are time-predictable and slip-predictable models, Markov models, characteristic earthquake models, self-exciting or doubly-stochastic or clustering point processes, and renewal models, all of which have been suggested as possible representations of earthquake sequences. In past practice, a random, memoryless (Poisson) process has been generally assumed in PSHA because of ease of application. Models with memory require more detailed knowledge and understanding of earthquake processes, which is often not available.

The impact of nonpoissonian behavior on site hazard may or may not be important.

Characteristics of seismicity for which only a few modeling alternatives and estimation procedures exist are the variations of earthquake rates in space (nonhomogeneity) and in time (nonstationarity). Spatial variations are especially important and difficult to estimate in regions where the stress-generating process and the causative geologic features are not well known. This includes most of the eastern and central United States where we lack a thorough understanding of the physical processes that control earthquake occurrence rates and hence nonhomogeneity. A typical approach in this instance is to define seismogenic provinces as geographical regions within which the seismicity is assumed to be homogeneous. Models of this type are popular because of their simplicity. However, hazard results are sometimes sensitive to the configuration of the seismogenic provinces and to the assumption of homogeneous activity within each province.

Temporal variations of seismicity ranging from long term (hundreds or thousands of years) to short term (weeks or months) are currently ignored, but understanding these variations will provide a basis for more credible hazard estimates in the future. An important example, which is now handled at an intuitive level in the process of defining homogeneous seismogenic provinces, is that regions that have been quiescent in the recent past--say during at least the period of the historical record--may suddenly become active in the next few decades.

An often influential modeling choice is that of the type of probability distribution of earthquake magnitude, including numerous variations on the distribution of one or several characteristic values. In practice, simple models such as the truncated exponential law should be preferred, unless such models are overshadowed by clear physical or statistical evidence.

Up to now, work on statistical earthquake occurrence has concentrated on model formulation and parameter estimation. New models, with spatial and temporal variation of seismicity and with various types of probabilistic dependences, should continue to be developed, but priority should perhaps be given to studying procedures for the validation and comparison of models on the basis of available data. Promising future directions can be summarized as follows:

1. Model Development. More work needs to be done on the representation of spatial and temporal nonhomogeneity of seismicity, including physical understanding of the mechanisms involved, earthquake source identification and variation of recurrence parameters at various geographical scales. This is an issue of importance in regions where seismogenic features are not well known. Nonstationarity at the scale of interest for PSHA, typically a few centuries in the past and a few decades into the future, should also be studied more closely. Earthquake catalogs as well as geologic paleoseismicity data should be analyzed for various features, including trends, gaps, migrations and characteristic episodes, and these phenomena should be accounted for in PSHA.

2. Model Validation and Comparison. Statistical techniques can be used to validate and compare models based on historical data. For example, various goodness-of-fit statistics can be developed using the method of cross validation, which is based on how well a subset of the data is predicted when the model is fitted to the remaining data. This can be taken as a measure of predictability of future earthquakes when the model is fitted to past seismicity. Modeling assumptions that are responsible for lack of fit should also be identified. Such statistical techniques can be guided by an understanding of the physical mechanisms that are involved in earthquake generation.

STRONG MOTION SEISMOLOGY

Currently, PSHA commonly employs statistical regression developed to construct models for ground-motion and response spectra. Relatively little use has yet been made of the emerging results from the physical modeling approach to strong ground-motion prediction. Opportunities exist for future development in both these areas.

The collection of additional data on strong ground-motion is basic to reduction of uncertainties associated with ground-motion models. Operation of the strong motion networks in the United States and worldwide is essential, and expanded networks are desirable because of tremendous gaps in our knowledge. Particular uncertainties remain in our knowledge of motion from large earthquakes ($M > 7$) in the western United States and from all sizes of earthquakes in the eastern United States. In addition, strong motion data are needed for many generic problems, including coherence of ground motion, dependence of ground motion on depth, type of faulting, site effects, and attenuation.

Several physical phenomena contribute to produce an observed accelerogram, such as shown in Figure 6.1. If one follows the physics of the problem from the source to the site, one has to deal first with the geometrical characteristics of faulting (obtained from geology), with dynamic characteristics of faulting, with the effects of seismic waves as they propagate from the source to the site, and with effects of surficial geological deposits and topography at the site. The following discussion considers these effects and how they can be modeled. An example of such synthesis is shown in Figure 2.1 also.

Physical Modeling Approach

Earthquakes are caused when the rocks on opposite sides of a fault slip suddenly. The earthquake can then be characterized by the size, shape, depth, and orientation of the fault area that slipped during the earthquake, as well as the amount and direction of slip. In addition, there are dynamic parameters, such as rupture velocity and rise time or coherence of slip, which are functions of the stresses acting on the fault and the physical properties of the rock within and adjacent to the fault zone.

Recently, it has become possible to estimate the time history and the spatial distribution of slip on the fault plane for exceptionally well-instrumented earthquakes. Figure 6.2 shows a model for the distribution of slip that occurred in the October 15, 1979, earthquake

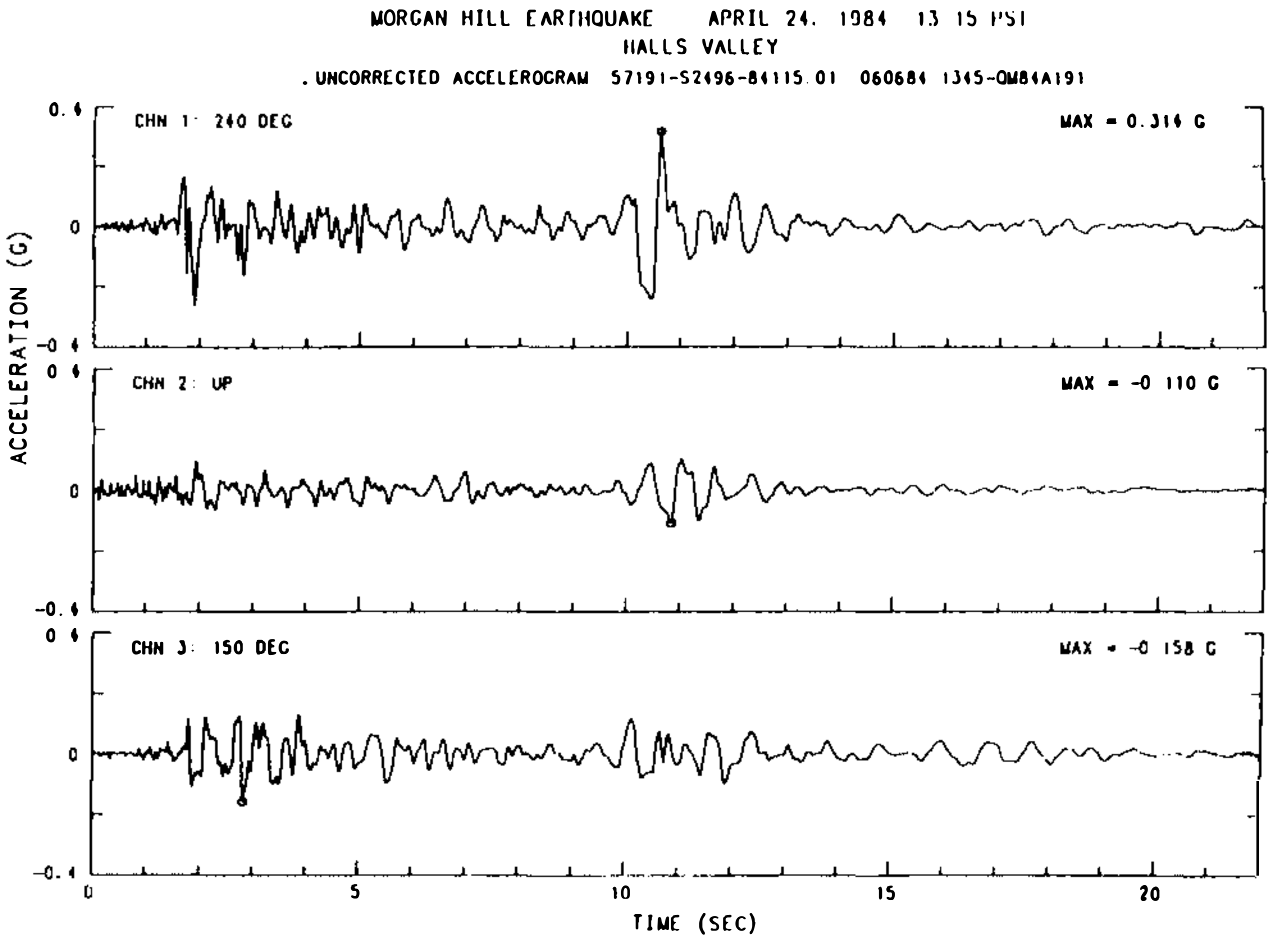

FIGURE 6.1 Processed data from the strong-motion records of the Morgan Hill Earthquake of 24 April 1984, Part I. ground-response records. (Office of Strong Motion Studies, 1986.)

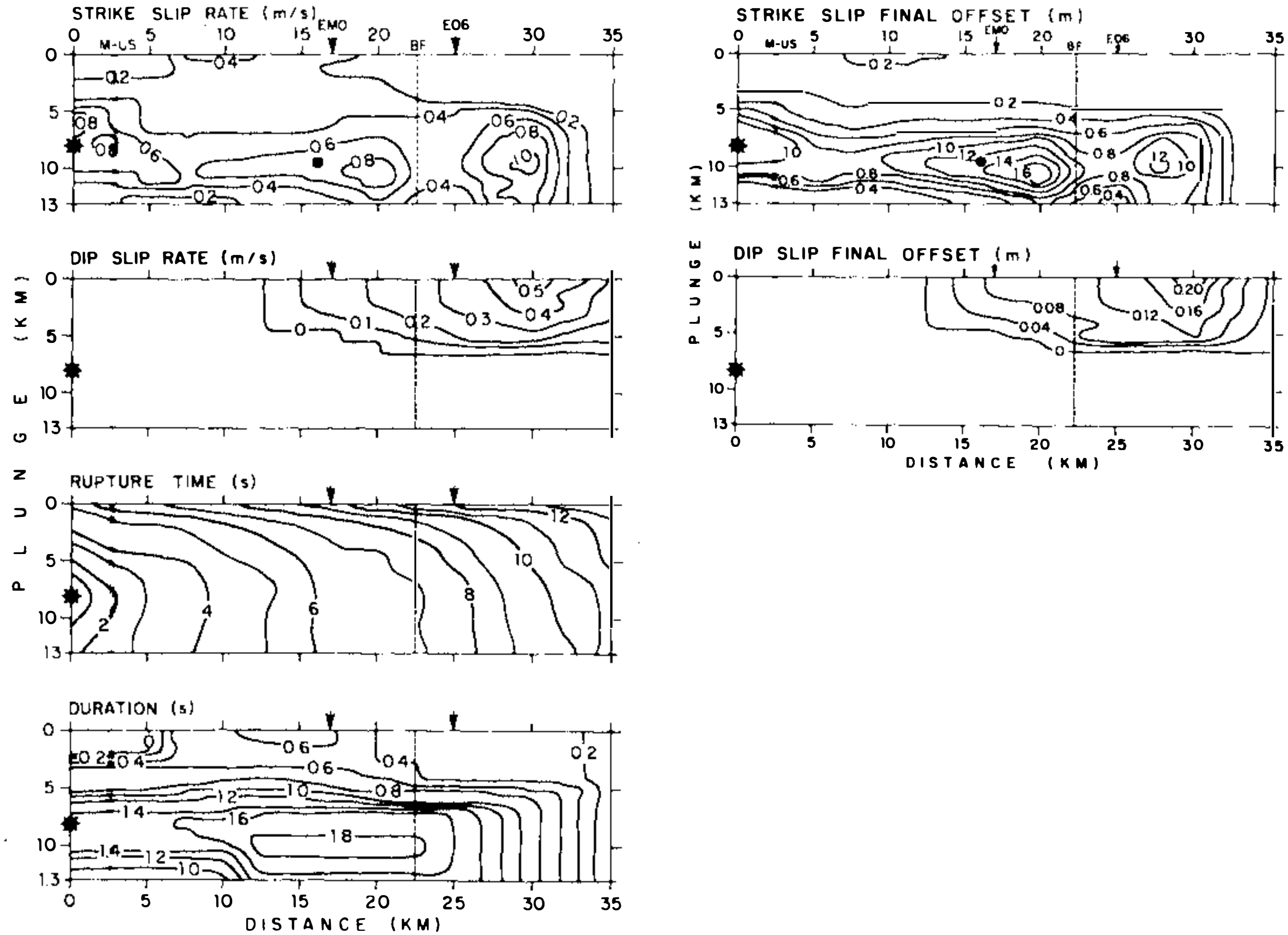

FIGURE 6.2 Model of fault slip distribution, Imperial Valley, October 1979. (Archuleta, 1984.)

in Imperial Valley, California. During that earthquake, the dynamic rupture parameters and the slip distribution were highly variable over both the length and depth of the fault plane. This variability was an important factor in determining the characteristics of the strong shaking during the earthquake. Smaller scale variability of the amount of offset on the fault may be present, but could not be resolved for this earthquake. These smaller scales would generate high frequency ground motions that are important for seismic hazards. An important related problem is to separate the effects of wave propagation, and especially attenuation, from seismic source effects. We need to characterize this variability for more earthquakes and to understand its consequences for strong motion estimation.

Wave propagation in the earth can be modeled using several approximations with increasing degrees of complexity. A simple approximation is propagation of seismic waves through a flat layered earth. This approximation is widely employed in all aspects of seismology, and is usually quite successful for many purposes (e.g., Figure 6.3). A second approximation includes the effects of large-scale deviations from a flat layered model. Models for these effects are still limited in the geometries that they can handle. The third is the effect of random variations on all scales because it is not possible to describe the inhomogeneities of the earth in sufficient detail to calculate the exact effects explicitly. Improved models and experimental verifications for the scattering effects of random perturbations in the velocity of the seismic waves are needed. The fourth aspect of wave propagation, which is crucial to describing strong motion, is attenuation, caused by the absorption of energy from a wave as it travels through the earth. Random scattering also causes apparent attenuation, and other wave propagation phenomena affect the amplitudes of seismic waves. These and source effects still need to be sorted out from the anelastic absorption of energy. The success in computing these effects depends on how thoroughly the seismic properties of the earth between the earthquake source and the site are known, and sometimes, the speed and memory of the available computers. Research needs to expand the capabilities and improve the efficiency of available techniques for these aspects, and to provide for multiple phenomena to be effectively accounted for.

The term "site effects" refers to wave propagation and attenuation in the immediate vicinity of the site. The boundary between a site effect and a propagation effect is not always clear cut, but it is nevertheless useful to discuss them separately. Site effects can include modification of seismic waves by the local sedimentary cover, the effect of the alluvial valleys, the effect of local topography, and effects of the water table. Recordings of the Mexican earthquake, September 19, 1985, in the Mexico City area, provide a striking example of site effects as shown in Figure 6.4. Mathematical techniques have been developed to handle the effects of a layered structure at the surface, of differing spectra at nearby stations on differing types of geological outcrops, and of local topography, including valleys, ridges, and small alluvium-filled valleys. Additional application and verification of these methods and experimental studies are needed.

In principle, the combined understanding of earthquake source physics and wave propagation allows computation of synthetic seismograms to arbitrarily high frequencies for any location.

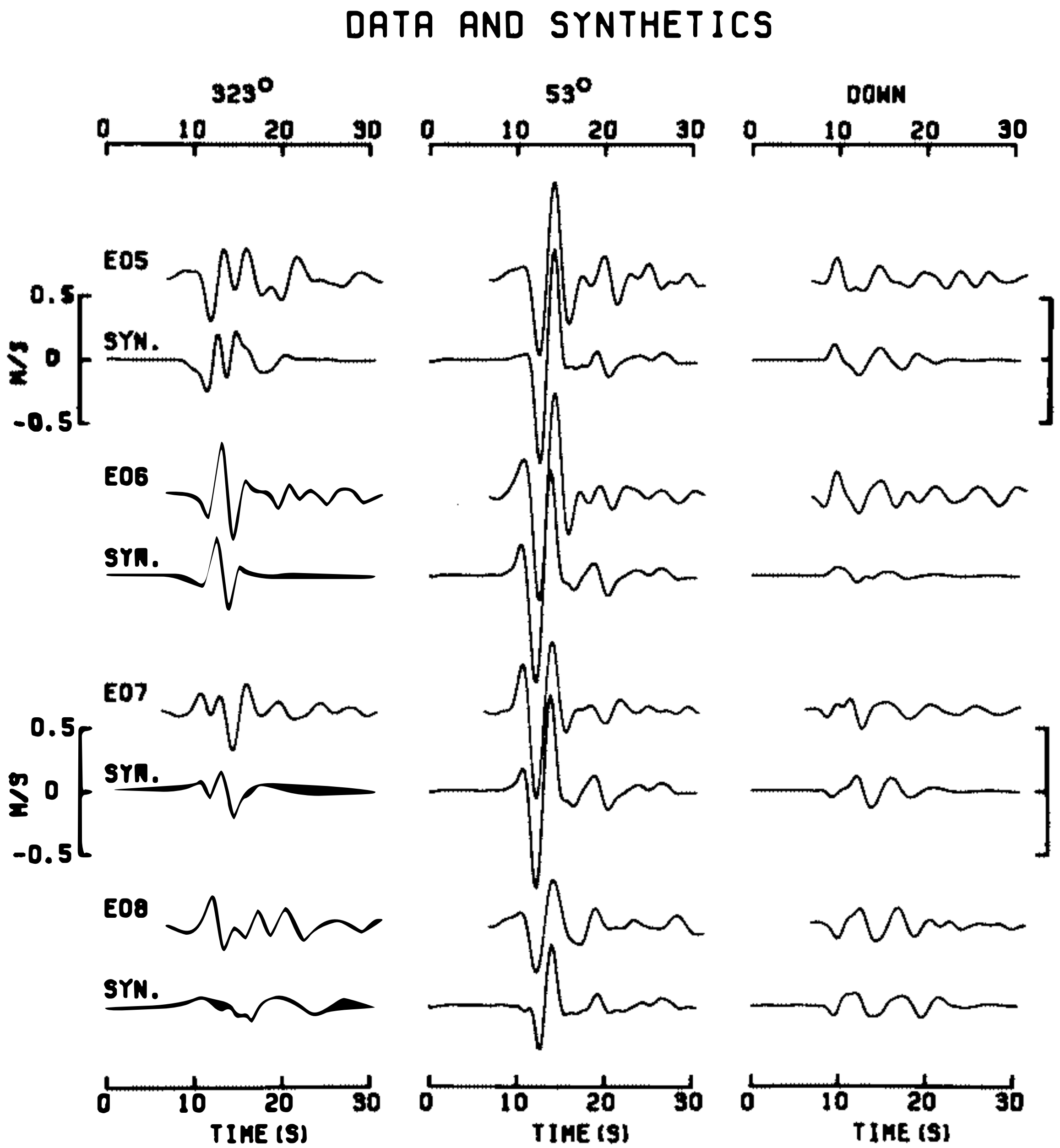

FIGURE 6.3 Comparison of observed and computed ground velocity at four sites in the October 1979 Imperial Valley earthquake (Archuleta, 1984).

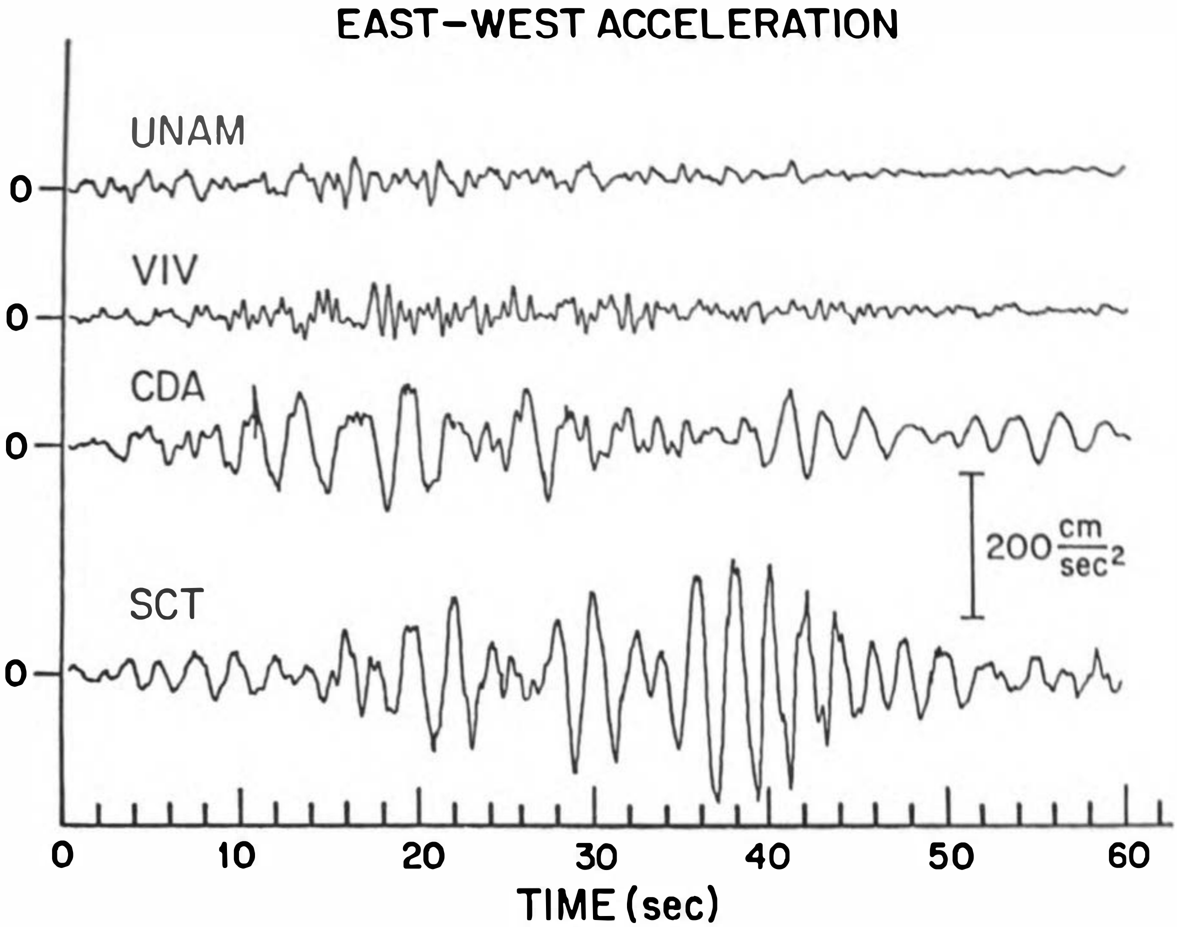

FIGURE 6.4 Most significant one-minute segments of the east-west acceleration recorded on the free-field accelerographs in Mexico City. No time correlation exists between these traces (Anderson et al., 1986). The UNAM record was taken on a recent basalt flow; the VIV was recorded on firm alluvial and lake deposits; the CDA and SCT records were recorded on deep, soft, lake bed deposits. These four stations are separated by 10 km or less, and are 300 km from the earthquake source.

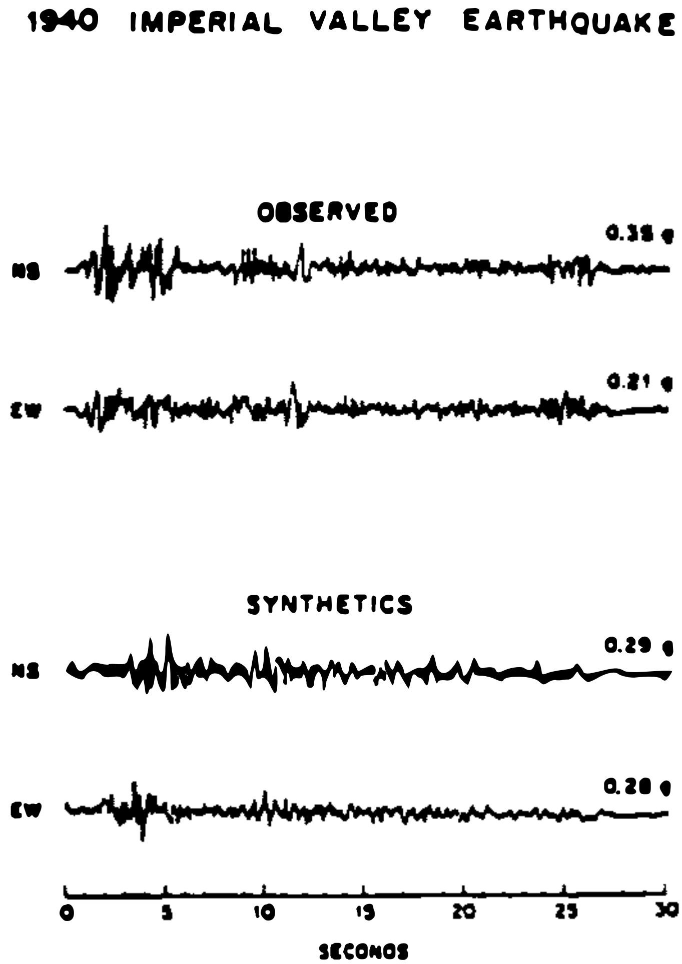

FIGURE 6.5 1940 Imperial Valley earthquake. Observed and simulated acceleration records at El Centro station (Munguia and Brune, 1984).

The calculation of synthetic seismograms has been a very active area in theoretical and computational seismology over the last two decades. Several methods are available. Some methods employ sophisticated wave propagation calculations (see, for example, Figure 6.3), others synthesize seismograms for large earthquakes from recordings of small earthquakes (see, for example, Figure 6.5). For some purposes, a random time signal generated with the desired spectral characteristics may be appropriate. All these techniques have shown some success and merit further development.

As summarized above, many analytical tools are under development that ultimately will provide a capability to take any hypothetical earthquake and generate seismograms and corresponding spectra that incorporate an understanding of all the physical phenomena, as they apply in the region of interest. Research emphasis has been in developing and testing the quantitative tools necessary for this endeavor. A quantitative description of uncertainties is needed. However, there is reason for confidence that this physical approach will eventually be the best way to minimize the uncertainties that must always be present in anticipating ground motion for future earthquakes.

Statistical Regression Analysis

In nearly all PSHA, up to the present, the most common method for estimating ground-motion distributions has been the least squares regression analysis. In this procedure, past recordings of strong motion are used to develop an empirical function to describe various parameters of ground motion as a function of the earthquake magnitude, distance from the fault to the site, and sometimes other parameters. Figure 6.6 shows an example of one regression model. This method is appropriate when sufficient data of the proper fault type, magnitude and distance range, soil conditions, and other parameters are available. If appropriate data are sparse, empirically derived coefficients may not be significant, implying uncertainty in the form of the model and consequently in estimated hazard. Physical models of the type outlined above may help reduce this uncertainty.

Recordings of strong motion reflect the combined effect of a variety of source, path, and site characteristics. Because of difficulties in isolating the effects of each of these factors, the data are usually sorted according to fairly generalized characteristics (e.g., site condition, fault type).

Among the factors that often are not explicitly included by empirical methods are sense of slip on the causative fault, stress drop, fault roughness, multiple types of seismic waves, wave attenuation and dispersion, anisotropy in the geological and seismological structure of the earth, deviations from flat structure, topography, alluvial valley or basin effects, and nature of near surface material. These omissions contribute to a significant amount of scatter in the data relative to the predictions. Physical models may provide insights in the predictive application of PSHA that will reduce this scatter. However, because some of these factors are not predictable in advance of an earthquake, including them in the PSHA can add tremendous complication with little, if any, demonstrable benefit. Simply put, the price that one pays for using empirical observations to

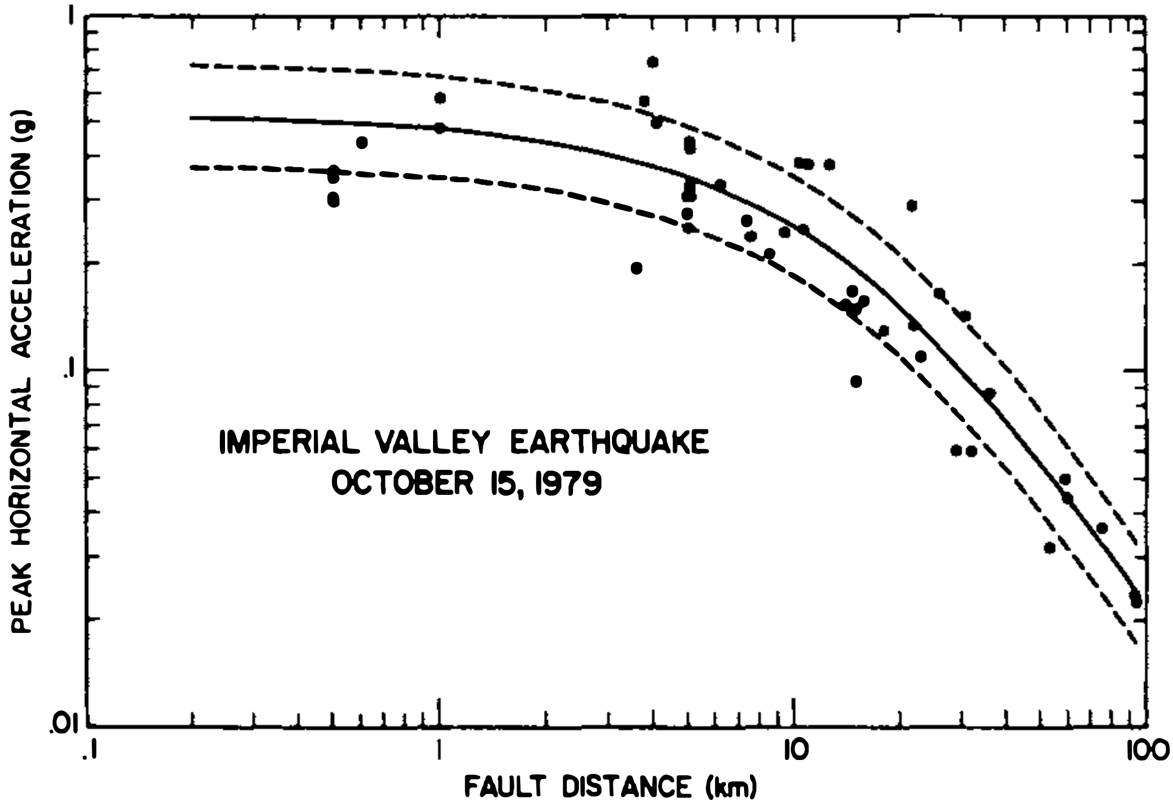

FIGURE 6.6 Observed and predicted mean horizontal peak accelerations for the 15 October 1979, Imperial Valley earthquake, plotted as a function of distance from the fault (Campbell, 1981).

predict ground motions is a considerable uncertainty (statistical scatter) in the derived empirical relationships. The explicit incorporation of this uncertainty into PSHA is standard practice.

A current statistical practice for estimation of ground-motion is referred to as a substitution method. An example would be combining a relationship between peak acceleration and seismic intensity with a relationship between seismic intensity and distance (possibly based on data from a different region than the first relationship) to obtain a relationship between peak acceleration and distance. Such substitutions can produce biased results, and furthermore only use part of the total data set. Methods should be developed that simultaneously and correctly process information from all sources and of all types: statistical and physical, on macroseismic intensity and on peak instrumental quantities, from the region of interest and from other regions. Other areas where improvement is needed are the treatment of anisotropy of attenuation and the quantification of local amplification effects.

The most immediate need in the area of empirical estimates of ground-motion is to obtain and examine more detailed data on fault rupture properties and site conditions, and to determine the extent to which these factors influence ground motions. This can be done in part with existing strong motion data, e.g., by determining the soil properties at stations where accelerograms have recorded past earthquakes. Doing so will help guide the physical studies on ground motion that will be most useful for PSHA. Examination of the scatter about predicted ground-motion estimates should be made; physical models and statistical analyses will help identify causes of large scatter and outliers, and may help establish any truncation of the ground-motion distribution (i.e., an upper limit, demanded by physics, to the ground-motion parameter, which is employed in the hazard analysis). Both the distribution and any truncation level are critical to hazard estimates. Also, more sophisticated methods of regression analysis that recognize the correlation of strong motion data (i.e., because of multiple components of motion, multiple records from the same earthquake, or multiple records from the same site) should become the standard. Finally, in regions such as eastern North America, use should be made of modified Mercalli intensity (MMI) to constrain ground motions for moderate and large earthquakes, as few strong motion records yet exist for this area. Methods that incorporate MMI (in particular, those that allow proper combination of MMI attenuation relations and MMI-to-motion-parameter correlations) need to be developed and widely used, for MMI to be given appropriate weight in estimating ground-motions.

PSHA METHODOLOGY AND APPLICATIONS

There is no consensus on which ground-motion parameters are most useful for predicting damage. For example, for equal values of peak accelerations, a large earthquake causes more damage than a small earthquake, with the differences related to the longer duration of shaking in larger earthquakes, and the different spectral content of the seismogram. Because standard shapes used to characterize the pseudo-velocity response spectra for design are generally consistent with earthquakes in the magnitude 6 to 7 range, these standard shapes will tend to overpredict damage for smaller magnitude events, and may underpredict damage for larger magnitude earthquakes. This is what leads to the need for disaggregation, which is the process of identifying which types of earthquakes contribute to the hazard in the hazard curve at the probability and amplitude levels selected for the design of a structure.

This also leads to the need to identify parameters, which can be derived from the accelerogram, that are better than peak acceleration as predictors of seismic damage. The response spectrum of an accelerogram is certainly better, but a better understanding of the relationship between the response spectral ordinates at various frequencies and damage is needed. Furthermore, the response spectrum does not fully account for the effect of the duration of seismic shaking. Thus, additional developments in defining parameters that are better predictors of damage might be called for, eventually resulting in further reductions in the need for dissaggregation.

It has been acknowledged that because of the uncertainties in the inputs for PSHA calculations, there is instability in the estimates for the hazard curves at a site. These uncertainties are present for any type of hazard estimate, not just the Type III or IV PSHA. Still, these uncertainties may be too large to be acceptable for routine building design because if the input to the PSHA calculations, which is likely to be based on a Type III analysis, were left to the hazard analyst, there may be excessively large variance in design levels. Prescription may provide a means to avoid these difficulties through building code applications. In brief, prescription would consist of the input, or the method of formulating the input that should be used for these hazard estimates. This would require obtaining a consensus from geologists and seismologists that the input is acceptable. Problems relating to the calibration of the calculations and the methods for handling site effects and regional variation of attenuation would need to be solved.

In situations where significant experience exists in the seismic design and response of facilities (e.g., for ordinary buildings in California), use can be made of this experience by calibrating probability-based seismic codes so that, on average, they require the same seismic resistance as previous codes. This avoids explicit studies on costs and benefits, and has the advantage that new designs are generally consistent with previous designs. The advantage of using a PSHA to specify the design requirements is that the procedure identifies high and low hazard regions and will require designs consistent with those hazards; a deterministic approach might not. Work on code calibration should be undertaken to provide a consistent transition for new seismic codes based on PSHA.

We have seen above that one of the main strengths of the PSHA methodology, especially the Type IV, is that the full range of models and hypotheses about the seismicity can be easily incorporated. However, most current PSHA transmit only single parameter representations for the ground motion and the resulting hazard curve represents an aggregation over a variety of distances and magnitudes. A Type V seismic hazard analysis overcomes these difficulties. A Type

V analysis uses a Type III or Type IV PSHA to characterize ground-motion probabilities and to identify individual sources, distances, and magnitudes that contribute most to the seismic hazard at the probabilities and ground-motion levels that are critical to the structure. For example, the mean magnitude and distance of earthquakes causing exceedance of the 10^{-4} ground acceleration at a site can be calculated during the hazard analysis, as demonstrated by McGuire and Shedloch (1981). Ground-motion modeling procedures would then be employed to derive more detailed characteristics of the ground motion, including time histories if they are needed. A full Type V analysis will examine whether the detailed ground-motion representation is consistent with the ground-motion function used in the original PSHA. If not, the PSHA will be revised, a new set of source and distance parameters will be derived, and a new detailed ground motion will be computed. In other words, a full Type V PSHA is a recursive procedure that ensures compatibility between the attenuation function used in the PSHA and the numerical procedure used to calculate details of ground-motion for the selected seismic event. Under a hybrid procedure, the regulatory approval might be based on performance of the structure during the critical earthquakes rather than on the specific hazard curve(s), which form the basis for its identification. This procedure would have the advantage that the specific earthquakes identified would offer an intuitive check on the adequacy of the design level that is selected.

An additional advantage of the Type V analysis is that it allows a more complete inclusion of the seismogram, which is often needed in the design of critical facilities. Further development of Type V hybrids are needed in three areas. The first is to refine methods of selecting the individual earthquakes, which are used as a basis for design, from the density function that contributes to the hazard curve. The second is to ensure internal consistency of the synthetic seismograms and the attenuation function used for the PSHA analysis. The third is to evaluate the sensitivity of the critical earthquakes to the assumptions employed in the PSHA.

The lower-bound magnitude for use in PSHA is sometimes critical to the results. Studies should be undertaken to characterize the frequency content and duration of earthquakes in the magnitude 4 to 6 range, and to determine their damage potential for the facilities being analyzed. The PSHA need not include earthquakes that do not damage structures and equipment, and should accurately characterize the damage potential of small events to accurately characterize the hazard for the subject facilities.

The use of PSHA results to make seismic design or evaluation decisions requires special comment. Because these results typically portray probabilities of occurrence of various ground-motion levels, and there are usually significant conservatisms built into the seismic design process, the calculated probability of exceedance of a design ground motion is not the probability of failure of the facility. Thus, additional studies are needed for risk levels (probabilities of loss) to be inferred from PSHA results and the seismic design levels of structures.

In many instances, particularly for critical facilities, studies indicating probability of losses are desirable, and research is needed to reduce the uncertainty associated with this aspect of risk estimation. These studies would estimate the seismic resistance of the facility and determine the probability and consequences of failure. Cost-benefit studies indicate the appropriate seismic design or retrofit level on an economic basis. Decision analysis that addresses the health and safety and environmental impacts of alternatives, in addition to their economic impacts, and that make value judgments explicit can be used to provide insights for selecting alternatives that responsibly balance the risks and benefits. Studies of these types are recommended to help make appropriate design decisions for best use of human and economic resources.

For other instances where less critical facilities are involved or resources are not available to conduct full risk analyses, studies of lesser scope are recommended. For seismic code purposes, code calibration can be used to infer acceptable hazard probability levels from PSHA, but it is probably not appropriate to use these results to evaluate existing designs. (Half of all existing buildings have seismic safety below the median as inferred from the probability of the seismic design level. And relative studies alone should not be used to require upgrading of those buildings.) Where PSHA results alone are available for critical facilities, approximate techniques to estimate probabilities of failure, consequences, costs, and benefits of seismic upgrade (taking into account the remaining facility lifetime) should be undertaken to make decisions regarding the adequacy of existing designs. For proposed critical facilities subject to strict safety regulations, studies should be undertaken of possible future changes in the perception of seismic hazard (given its current uncertainty) before decisions are made on the appropriate design level. All of these recommendations are achievable with decision analysis and risk analysis methods used widely in the engineering and social sciences.

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APPENDIX A:

CHARGE TO THE PANEL

The Committee on Seismology, in 1984, requested the National Research Council to approve the appointment of a Panel on Seismic Hazard Analysis to conduct a study as specified.

The Panel on Seismic Hazard Analysis is to assess the capabilities, limitations, and future trends of probabilistic seismic hazard analysis (PSHA) in the context of alternatives.

The objective of SHA is to quantify for engineering design and public policy purposes the probability, p, that at a particular site a certain specified level of ground motion will be exceeded in the next n years, where p may be on the order of 10^{-1} to 10^{-5} and n may be on the order of 1 to 100 years or, in the case of nuclear waste disposal, on the order of thousands of years. A secondary objective is to define more or less quantitatively the uncertainty in that probability estimate.

Many engineering decision makers and several public agencies use, or are evaluating for future use, formal risk analyses. When seismic hazards are involved in these analyses, quantitative probability and uncertainty statements are requisite input. The panel should evaluate current seismic hazard analysis theory and application with respect to (1) its consistency with the wider, general use of quantitative risk analysis in science, technology, and public policy, (2) its technical merits in terms of applied probability and statistics, and (3) its relationship to the earth sciences and earthquake engineering. On one hand, scientists have argued that the field knows too little to make such quantitative statements and that, therefore, PSHA may "abuse" their science. On the other hand, given that some decisions must be taken, seismologists and other scientists have often been asked to take large responsibilities with respect to engineering decisions and public policies regarding seismic hazards, even when they may be lacking the information regarding costs, impacts, and alternatives that are crucial to the problems; PSHA has been presented as a way to transmit unequivocably to the responsible parties what earth scientists are uniquely qualified to evaluate: seismic probabilities and their current uncertainties.

The Panel on Seismic Hazard Analysis is to report to the Committee on Seismology in approximately two years for a presentation of its assessments and its recommendations.

APPENDIX B:

SUMMARY OF RESPONSES TO PSHA QUESTIONNAIRE

The first meeting of the Panel on Seismic Hazard Analysis was in March 1985. Briefings were presented that emphasized probabilistic seismic hazard analysis (PSHA), and these resulted in recognizing the need for an assessment of the factors involved in making such analyses. A questionnaire was developed to focus the deliberations of future meetings on needed improvements as perceived by a representative sample of the appropriate scientific and technical communities. The questionnaire was sent to 31 engineers and scientists, of which 25 responded, including 22 who answered questions specifically. The questions are given below, together with a summary of the responses. (The summary is intended to portray the main sense of the responses.)

QUESTION 1. What are the strong points of the conceptual and theoretical foundation of PSHA? What are the weak points?

Strong Points

1. PSHA provides a logical and consistent way to represent earthquake and ground-motion occurrences, utilizing and accounting for uncertainties in knowledge.
2. Allows scientists to express their uncertainty and represent it properly; it leaves the decision of "acceptable risk" to the policy makers, where it belongs.
3. Forces scientists to examine and define thought processes in a rigorous way.
4. Facilitates sensitivity analyses and comparisons among groups.

Weak Points

1. Methodology can be abused to get any answer the analyst wants. One respondent characterized this as an arbitrariness in the choice of a prior distribution in a Bayesian analysis.
2. Results may contain large uncertainty, which limits its usefulness.
3. Probabilities are calculated that are extrapolations of the data.
4. "Gut feeling" may be overridden by the formal mathematics.
5. The large uncertainties implied by PSHA may undercut the need for engineering studies.

QUESTION 2. What are the strong points of performing PSHA and what are the weak points?

Strong Points

1. Provides the most uniform and complete description of earthquake hazard, of all possible methodologies.
2. Allows the generalization of earthquake data to calculate probabilities of events that have not yet occurred.
3. PSHA informs the user about uncertainties.

Weak Points

1. Lack of data, or not all data (e. g., on fault slip) is used.
2. Lack of widely-accepted methodology.
3. Assumptions are not, or cannot be, verified.
4. Strong mathematics gives a false impression of rigor, precision, and scientific respectability that is not justified, based on the poor quality data available.
5. Conclusions may be accepted without good engineering or scientific judgment.
6. Not enough resources (money, time) are usually available to do the job correctly or fully.
7. Lack of familiarity breeds distrust.

QUESTION 3: Compare the different methods of performing PSHA with respect to the main advantages of each.

Many respondents did not understand this query and did not answer, while others gave inappropriate responses.

One person felt that difference in methods were not critical.

Several respondents expressed a strong need for incorporating geological and seismological considerations into PSHA.

QUESTION 4: How does PSHA, in general, transmit geological and seismological knowledge to users?

There was confusion regarding the word "transmit" in the question. It was meant as "capture" and some took that meaning, while others took it to mean "inform". In the latter instance, some respondents felt it was not necessary to inform users about geology or seismology.

QUESTION 5: Is the data base (historical seismicity, geology, microseismicity, strong ground motion) adequate to perform PSHA (a) on the west coast, (b) in the central and eastern United States? If not, what additional data could be collected to alleviate this need?

(a and b) A histogram of the responses showed a tendency to believe that the data are more nearly adequate for the west coast than the east coast of the United States.

Additional research and data that are needed include geologic studies including fault locations and slip rates; additional earthquake recordings; theoretical advances in PSHA methods, especially to give time histories; improved methods to incorporate characteristic earthquakes; and studies of earthquake fundamentals and of strong motion for the eastern United States.

QUESTION 6: What procedures other than PSHA are preferable for specifying seismic design requirements of critical and other facilities? What are the advantages of these over PSHA?

The responses to Question 6 were plotted as a histogram, which showed: That 25 percent did not name any preferable procedures; that 25 percent mentioned preferable procedures for non-critical structures; and that 50 percent named an alternative for critical structures.

In general, one alternative was to use a "deterministic" designation of an extreme earthquake for design purposes, including an estimation of its probability. Some advantages were: This procedure would be more easily understood by policy makers; deterministic procedures were less likely to contain aberrant assumptions, and deterministic methods should be used while the probabilistic methods are being developed further. An additional suggestion was for a highly qualified group to provide recommended guidelines for critical facilities on a region-by-region basis.

QUESTION 7: Is the product of PSHA (e.g., probabilities of exceedance versus ground motion amplitude) a meaningful statement of likelihoods of future ground shaking occurrences for any level of likelihood? If not, why? What additional parameters do you think are needed?

There were two, at most, completely negative replies to the first part of the question, while the balance of respondents expressed an affirmative opinion with constraints, such as the following: when properly performed, with the inclusion of geologic and seismologic considerations, with an adequate data base, and in conjunction with a deterministic analysis. Four respondents felt the limits on annual frequency should not be less than 10^{-4} or 10^{-3}.

Eight respondents expressed the need for additional parameters, such as time histories, spectra, duration and frequency content and/or dominant frequency, and number of cycles of strong shaking and duration. These respondents felt that the peak ground acceleration was an inappropriate parameter to use for design purposes. One person felt that the Modified Mercalli Intensity scale was also a poor measure.

QUESTION 8: Should estimates of probabilities of exceedance be accompanied by a statement of uncertainty, e.g., reflecting various methods of analyses, alternative interpretations of the data, different tectonic models, and differences in expert opinion?

Question 8 was answered by 21 of the 22 who answered questions. Fifteen answers are an unconditional "yes" (of these, at least 5 are emphatically positive), whereas 6 indicate reservations as to the appropriateness of quantifying uncertainty. Specifically, 3 of the latter 6 respondents find it desirable to report uncertainty within the research community, but warn that such uncertainty would cause misinterpretation by engineers and confusion to the public and the media. One person suggests that "statements of uncertainties would introduce even greater levels of doubt about the validity of any probability figures that would exist anyhow" and advocates the use of "best estimates." Another respondent opposed the explicit quantification of uncertainty on seismic hazard results and suggested that a caveat about the accuracy of single estimates should be sufficient. The basic reason for rejecting a detailed representation of uncertainty is that it would be difficult and inappropriate for policy officials to choose among alternative methods and results. Finally, among the critics, one respondent warns that disclosure of the large degree of uncertainty on seismic hazard might invite sloppiness in subsequent engineering work and undercut the need for advancing structural analysis techniques.

Most of those who have responded in the affirmative have stressed the importance of (1) explicitly stating alternative modeling assumptions and data interpretations, (2) identifying the main sources of uncertainty on seismic hazard, and (3) with multiple experts, preserving the diversity of professional opinion. Additional comments from the same group of respondents are as follows.

- An agreed-upon methodology and a standard format for uncertainty quantification and reporting should be developed.
- By showing sizes and sources of uncertainty, PSHA provides guidelines for the efficient investment of additional resources.
- One should distinguish between uncertainty on parameters because of limited data and uncertainty resulting from model selection and expert diversity.
- The mathematical statements of uncertainty may not always be valid estimates of the actual uncertainty.

No respondent has indicated ways to deal with uncertainty on seismic hazard in the context of decision making. This difficulty has motivated some to suggest that, for general use, best estimates are sufficient. The decision-theoretic format advocated by one respondent is capable in principle of accounting for uncertainty in the exceedance probabilities, but more work is needed before practical rules can be obtained from it.

QUESTION 9: How should PSHA be used? To specify appropriate design levels? To check design levels determined by other methods? Does this use depend on the type of facility being considered?

Thirteen respondents expressed the opinion that PSHA should be used to specify aggregate design levels; four were undecided; one felt it should be used partially; and one was completely negative. The same response was given to the question about checking the design levels determined by other methods.

Regarding the question about the type of facility being considered, respondents expressed the following opinions: it is useful to express an operation basis event; it should be used with a safety factor of design; fragility should be included; deterministic methods should also be used until PSHA is better developed; it should be used to check the consequences of structure failure; PSHA should be used to specific aggregate design if the budget is adequate, otherwise it should be used to check the design determined by other methods; it should be used with a characteristic earthquake; it should be used when the data are adequate; it should be used for minor facilities; PSHA should be combined with other information; and the use of PSHA should not depend on the type of facility.

QUESTION 10: Do you think terms, such as "maximum credible earthquake", can be sufficiently well-defined to be of use in specifying seismic design requirements for facilities?

The basic answers to Question 10 can be summarized as follows:

Yes	4
Probably	8
Probably not	4
No	4

The split between affirmative and negative responses was 12 to 8, respectively. However, the split was not nearly as marked as the results might suggest. In fact, of the 14 responses that also provided the basis for their answer, the results can be summarized as follows:

Yes, if the faults are well known	4
Yes, if the maximum credible earthquake (MCE) is defined probabilistically	5
No, because the maximum event should be defined probabilistically	4
No, our state of knowledge is too poor	1

Note that 9 of the responses voiced essentially the same opinion that the MCE should be placed within a probabilistic context. Whether or not the MCE is typically associated with a probability of occurrence is debatable. However, the suggestion was clearly given that the maximum event should be tied to a recurrence interval or probability of occurrence.

QUESTION 11: Would you be interested in attending a panel meeting to discuss these issues?

Most responses to this question were affirmative. Three respondents, representing a wide range of opinion, attended meetings of the panel to discuss PSHA and its use.

QUESTION 12: Additional comments. (Made in response to questionnaire)

Some pertinent additional comments are as follows.

- The probable intensities of earthquakes should be separated from frequency of occurrence.
- Probability theory applies very precise mathematics to a data base that is incomplete and imprecise, and erroneous assumptions can ruin the analysis.
- When we speak about <u>engineering</u>, a job within the state of the art, we are not seekers of <u>ultimate truth</u>; there is a tendency to equate mathematical sophistication with increased accuracy of hazard calculations, sometimes at the expense of physical and geological reasoning.
- PSHA has been abused in the past, and it is clear that no theory of extreme-value distribution can be a substitute, in any way, of geological and seismological investigations.

- The panel should recommend the research required to identify different types of geology and stress conditions to give physical meaning to the statistical statements other than blind probabilities based on inadequate data.
- Major extensions of conventional PSHA are needed to deal with lifelines and spatially extended facilities.
- The Division of Geology and Land Survey (Missouri) believes that the probabilistic seismic hazard analysis (PSHA) conceptually is the best method to establish seismic design criteria (e.g., for new dams) to reflect various levels of risk.
- Policy officials can accept uncertainties regarding the definitive character of any analysis, so long as there is a general accepted methodology for arriving at the opinion.
- In the northeast, where the cause of seismic activity is strictly a matter of speculation, it may be more appropriate to utilize expert opinion and historical data rather than the PSHA to influence public policy decisions, and earthquake data must continue to be collected until uncertainties with PSHA can be lessened.
- Efforts should be made to help analysts understand the seismological, geological, statistical, and other assumptions in the PSHA.

APPENDIX C

PROBABILISTIC SEISMIC HAZARD CALCULATIONS

The most robust evaluation of hazard is given by the equation:

$$\nu_{\underline{A}c\underline{a}} = \int_{\underline{X}} \int_{\underline{\Theta}} d\nu \; (\underline{\Theta}, \underline{X} \; | \underline{S})$$

in which $\nu_{\underline{A}c\underline{a}}$ is the seismic hazard calculated as the expected number of specific occurrences at a site in future time interval T. In practice, this expected number is approximately equal to the probability of one or more such occurrences. It can be proven* that $\nu_{\underline{A}c\underline{a}}$ is always an upperbound to this probability; practically, it is a close approximation whenever that probability is less than about 10 percent. For engineering applications this condition will virtually always apply because occurrences with low probabilities are of interest. The notation $\underline{A}c\underline{a}$ indicates the occurrence of some vector of ground-motion or other earthquake motion characteristics $\underline{A}$ within some particular interval, $\underline{a}$. The single most common example is when $\underline{A}$ is the (scalar) peak ground acceleration and the interval $\underline{a}$ is an open interval such as "greater than 0.2 g." The notation allows for more general cases; for example, those in which one is interested in a range of ground-motion intensity and duration, a set of spectral ordinates over a broad frequency band, or other multidimensional representations of ground motion.

In the equation given above, the vector $\underline{\Theta}$ represents a set of parameters describing the earthquake energy release, often simply the scalar magnitude (measured in some convenient scale). Again, the use of a vector implies that we could extend the description of the energy release to as many parameters as we wish, recognizing the practical constraint that we must be able to make predictive statements about the relative frequency of the values of these parameters. The vector $\underline{X}$ represents the location of the earthquake energy release, e.g., the location in space of its epicenter. The integrals over values of $\underline{\Theta}$ and $\underline{X}$ are made over the range for which $\underline{A}$ ($\underline{\Theta}$, $\underline{X}$) is contained in $\underline{a}$. The vector $\underline{S}$ represents the specific seismic and tectonic history in the region. For example, this might be the information that "a magnitude 7 event occurred at the center of fault n 21 years ago today." The vertical line preceding the $\underline{S}$ is read, of course, "given

*The simple proof involves comparing term by term the expected number of events versus the probability of one or more events. Each term (i.e., associated with 1, 2 . . . events) in the former is greater than or equal to the corresponding term in the latter.

that." The integrand $d\,\nu(\underline{\Theta},\underline{X}\,|\underline{S})$ is to be interpreted loosely as the expected (future) number of events with source parameters $\underline{\Theta}$ centered at location $\underline{X}$, given the current seismic history, $\underline{S}$. Strictly, this is a differential rate, i.e., a rate per square or cubic kilometer or a differential interval of the source parameters, $\underline{\Theta}$ to $\underline{\Theta} + d\underline{\Theta}$.

The function $\underline{A} = g\,(\underline{\Theta},\underline{X})$ is a ground-motion prediction equation that predicts the value of the ground-motion parameters (e.g., peak ground acceleration (PGA) at the site of interest, given an earthquake with source parameters $\underline{\Theta}$ centered at location $\underline{X}$. In common practice, this may be as simple as regression equation

$$A = g\,(M,\, R)\epsilon,$$

in which M is magnitude in some convenient scale, R is distance from epicenter to site and ϵ is a random error term.

Finally, the integration is carried out over all values of possible locations of the earthquake ($\underline{X}$) and for given $\underline{X}$ over all values of the source parameters $\underline{\Theta}$ such that the predicted ground-motion parameters $\underline{A}$, at the site, will fall within the interval of interest: $\underline{a}$. For example, if one is considering the PGA level 0.2 g and a (differential) location of the earthquake 70 kilometers from the site, then the ground-motion prediction equation may imply that this acceleration level will be exceeded at the site if--and only if--the magnitude (M) exceeds 7, in which case this integral would be over all values of the source parameter magnitude above level 7. (If the ϵ term is included, higher values of ϵ will imply that lower magnitude values are adequate to cause $A \geq 0.2$ g and vice versa, hence, the need for a joint integration over M and Θ.)

Thus, the analytical calculation of seismic hazard is both simple and quite general. The use of vectors for $\underline{\Theta}$, $\underline{X}$, $\underline{A}$, and $\underline{S}$ implies that one can generalize seismic hazard analysis to include models in which the source is specified by 1, 2, or many parameters, in which the location of the earthquake can be in a plane or in a volume, and in which the ground-motion intensity can be a simple scalar or a vector of values. The inclusion of the conditioning statement $\underline{S}$ implies that one can use the model for the range of situations from pure memoryless (Poissonian) temporal and spatial behavior (in which case $\underline{S}$ would enter the equation only through calculation of the time-average rate of occurrence), through various slip or time predictable models, to earthquake predictions based on observed precursors and seismic history.

APPENDIX D

GLOSSARY

active fault: A fault that on the basis of historical, seismological, or geological evidence has a finite probability of producing an earthquake.

B-value: A parameter indicating the relative frequency of occurrence of earthquakes of different sizes. It is the slope of a straight line indicating absolute or relative frequency (plotted logarithmically) versus earthquake magnitude or meizoseismal Modified Mercalli intensity. (The B-value indicates the slope of the Gutenberg-Richter recurrence relationship.)

damage: Any economic loss or destruction caused by earthquakes.

design earthquake: A specification of the seismic ground-motion at a site; used for the earthquake-resistant design of a structure.

design ground-motion: (See "design earthquake.")

design spectrum: A set of curves for design purposes that gives acceleration, velocity, or displacement (usually absolute acceleration, relative velocity, and relative displacement) of a single degree of freedom oscillator as a function of natural period of vibration and damping.

duration: A qualitative or quantitative description of the length of time during which ground motion at a site shows certain characteristics (e.g., perceptibility, large amplitudes).

earthquake: A sudden motion or trembling of the earth caused by the abrupt release of slowly accumulated strain. The ground motion may range from violent at some locations to imperceptible at others.

exceedance probability: The probability that a specified level of ground motion or specified social or economic consequences of earthquakes will be exceeded at a site or in a region during a specified exposure time.

expected: Mean, average.

exposure: The potential economic loss to all or a certain subset of structures as a result of one or more earthquakes in an area. This term usually refers to the insured value of structures carried by one or more insurers.

intensity: A measure of the effects of an earthquake at a particular place. Different scales used to specify intensity are the Modified Mercalli, Mercalli, Rossi-Forel, Housner Spectral Intensity, and Arias.

loss: Any adverse economic value attained by a variable during a specified exposure time.

maximum credible: Term used to specify the largest value of a variable, e.g., the magnitude of an earthquake, which might reasonably be expected to occur.
mean: Average value of a set of data.
median: Middle value of an ordered list.
peak acceleration: Maximum value of acceleration displayed on an accelerogram.
peak displacement: Maximum value of displacement obtained or calculated from a record of ground motion.
peak velocity: Maximum value of velocity obtained or calculated from a record of ground motion.
response spectrum: A set of curves that gives values of peak response of a damped linear oscillator to earthquake motion, as a function of period of vibration and damping.
seismic hazard: Any physical phenomenon (e.g., ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities.
seismic risk: The probability that social or economic consequences of earthquakes will equal or exceed specified values at a site, at several sites, or in an area, during a specified exposure time.
variance: The mean squared deviation of a random variable from its average value.
vulnerability: The degree of loss to a given element at risk, or set of such elements, resulting from an earthquake of a given magnitude or intensity, which is usually expressed on a scale from 0 (no damage) to 10 (total loss).