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Computations of seismic hazard

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Abstract
Methodologies available for the calculation of seismic hazard are well established. The historical method requires only a catalog of historical earthquakes, appropriate attenuation functions for ground motions in the region, and site response functions; the deductive method requires, in addition, a description of possible faults and earthquake sources, and the parameters describing seismicity for those faults and sources. Uncertainties in interpretations can be handled explicitly through multiple hypotheses, leading to uncertainties in seismic hazard. Accounting for these uncertainties in seismic hazard computations leads to the most informed decisions for earthquake risk mitigation.

1. Introduction

Seismic hazard analysis is the computation of probabilities of occurrence per unit time of certain levels of ground shaking caused by earthquakes. This analysis is often summarized with a *seismic hazard curve*, which shows annual probability of exceedance versus ground motion amplitude. The results of a seismic hazard analysis can be convolved with a seismic fragility function, which quantifies the probabilities of various levels of damage to a facility as a function of ground motion, to give a *seismic risk analysis*, which indicates probabilities per unit time of different levels of failure or loss. Thus seismic hazard analysis is a fundamental input into the decision-making process for earthquake loss mitigation.

This paper summarizes the inputs required for a seismic hazard analysis and the methods available for calculation. Restrictions are also discussed, both on the inputs and results.

2. Inputs to seismic hazard analysis

As with any quantitative analysis, the inputs to a seismic hazard analysis are critical. It is the case for *all* inputs to the seismic hazard analysis that alternative interpretations must be made where significant uncertainty exists. Thus the analyst should make a «best» interpretation and should also represent uncertainties caused by lack of data or lack of knowledge either with a specified distribution or with alternatives. The most fundamental input required is a processed earthquake catalog for the region of study. This catalog must contain the locations, times of occurrence, and size measure of historical earthquakes. Where significant uncertainty exists on any of these quantities, they should be expressed for each earthquake. The catalog must be processed in the sense that duplicate events should be removed, foreshocks and aftershocks must be identified and tagged, and a uniform magnitude measure must be estimated for each event.

The second required input is a designation of active faults or earthquake sources in the region. Faults should be specified by geometry (in three dimensions), sense of slip, segmentation, and a function describing rupture length or area as a function of magnitude. Figure 1 shows a set of faults in Central California described for the study of seismic hazard at the Diablo Canyon Power Plant, and fig. 2 illustrates the logic tree that was developed to quantify the uncertainties in fault characteristics. Multiple interpretations were made of the

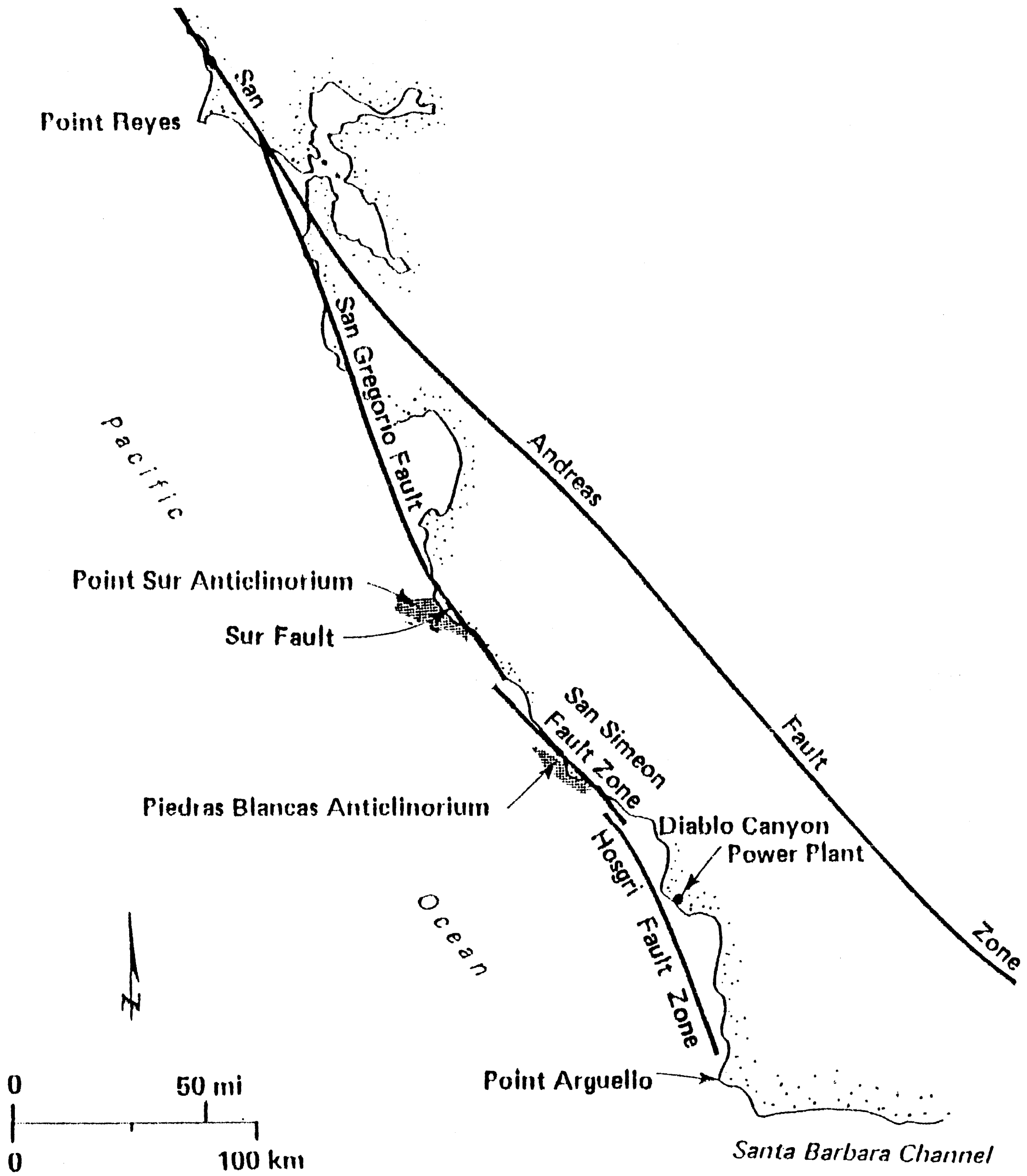


Fig. 1. Faults used in study of Diablo Canyon Power Plant (Pacific Gas and Electric, 1988).

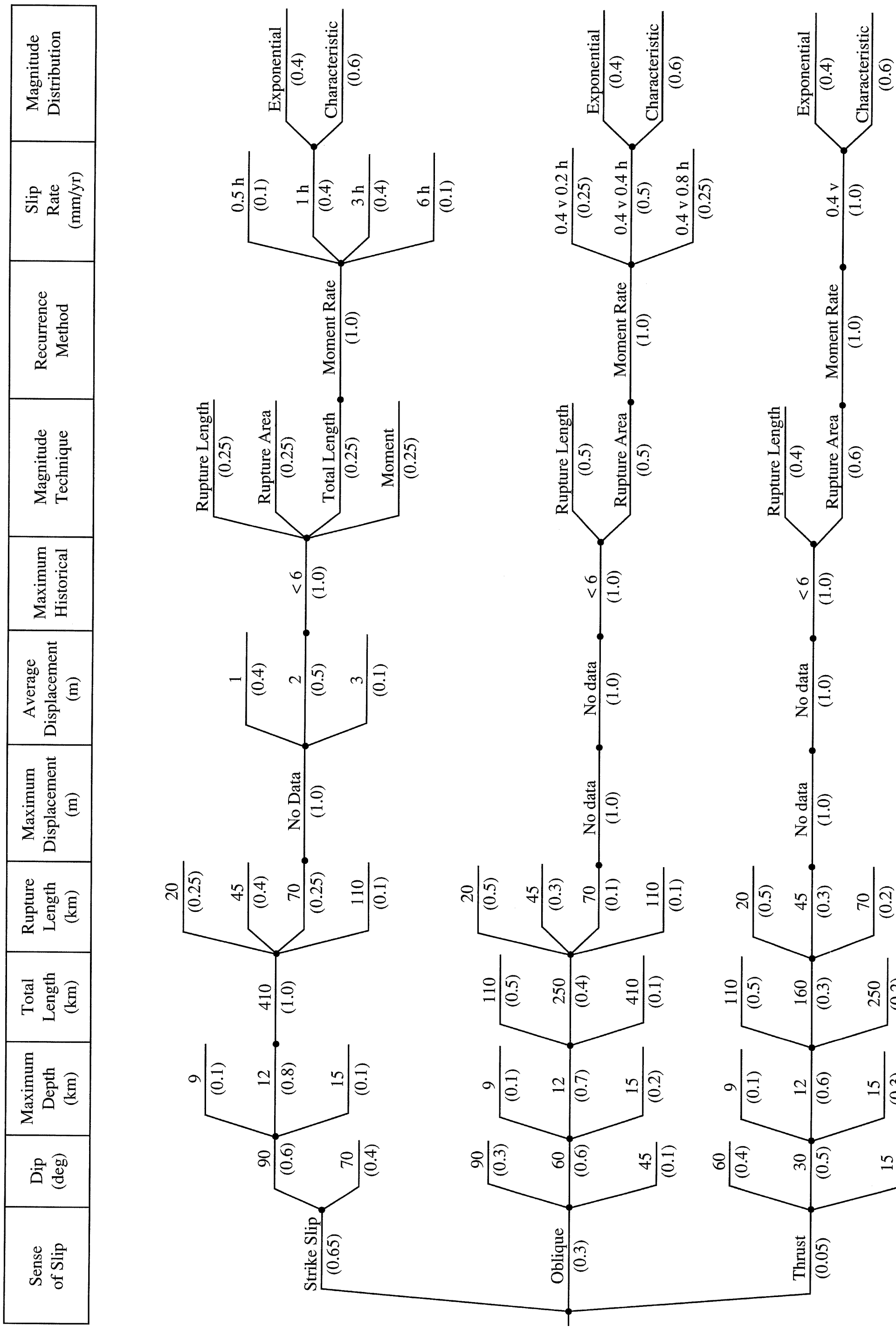


Fig. 2. Logic tree representing fault data (Pacific Gas and Electric, 1988). Values in parentheses are probabilities; h = horizontal component of slip rate; v = vertical component of slip rate.

sense of slip, dip angle, maximum depth, total length, maximum rupture length, average displacement per event, slip rate, and magnitude distribution for the Hosgri fault, which dominated the seismic hazard at the plant site.

If faults cannot be identified, the locations of possible earthquakes must be represented with areal sources. These are spatial areas within which earthquake characteristics are designated to be uniform. Figures 3 and 4 show two sets of areal sources for the Eastern United States that were determinated by two Earth Science teams in a project on seismic hazards for the region. The great difference in source geometries illustrates that is often important to obtain several independent sets of interpretations, rather than rely only on one, to span the range of scientific uncertainty on the locations of future earthquakes. In that particular study, six teams of earth scientists were used to span the range of interpretations. Along with the mapped spatial extent of areal sources, one must specify the depth of occurrence of earthquakes and any other characteristics (*e.g.* sense of slip) that might affect the associated ground motions.

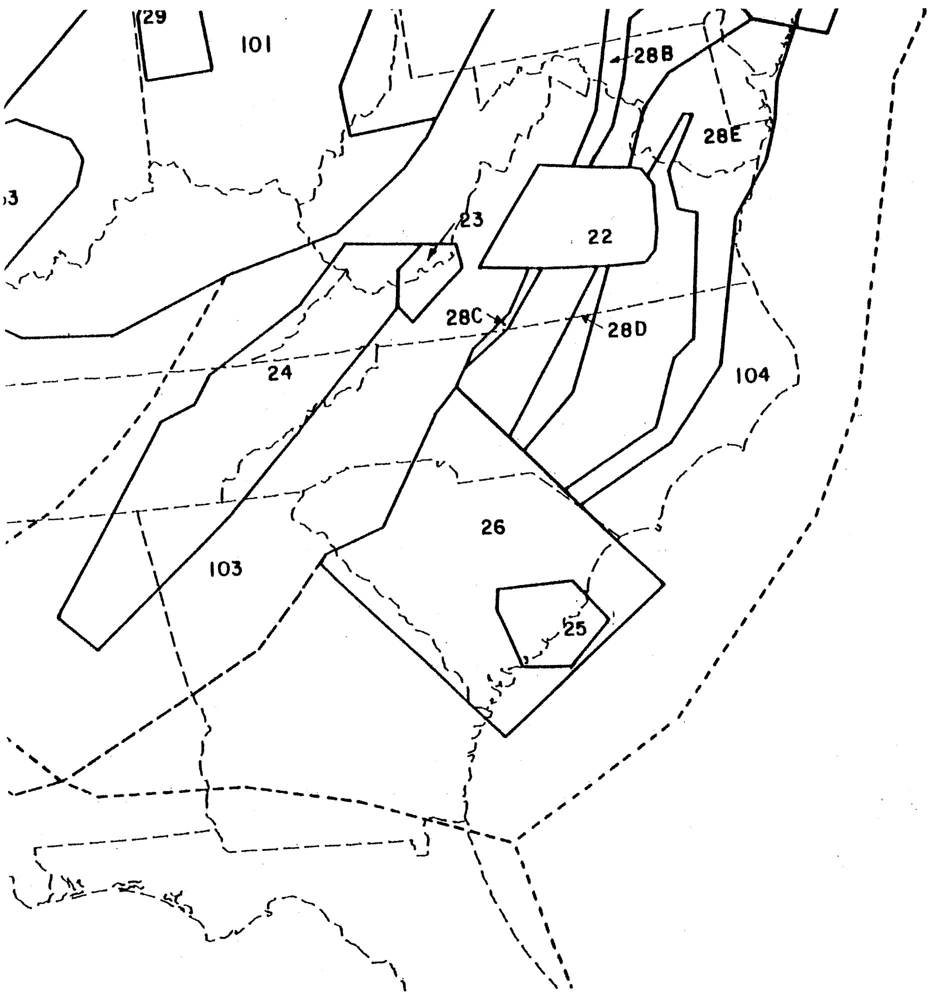


Fig. 3. Seismic sources in Eastern U.S., team I (EPRI, 1986).

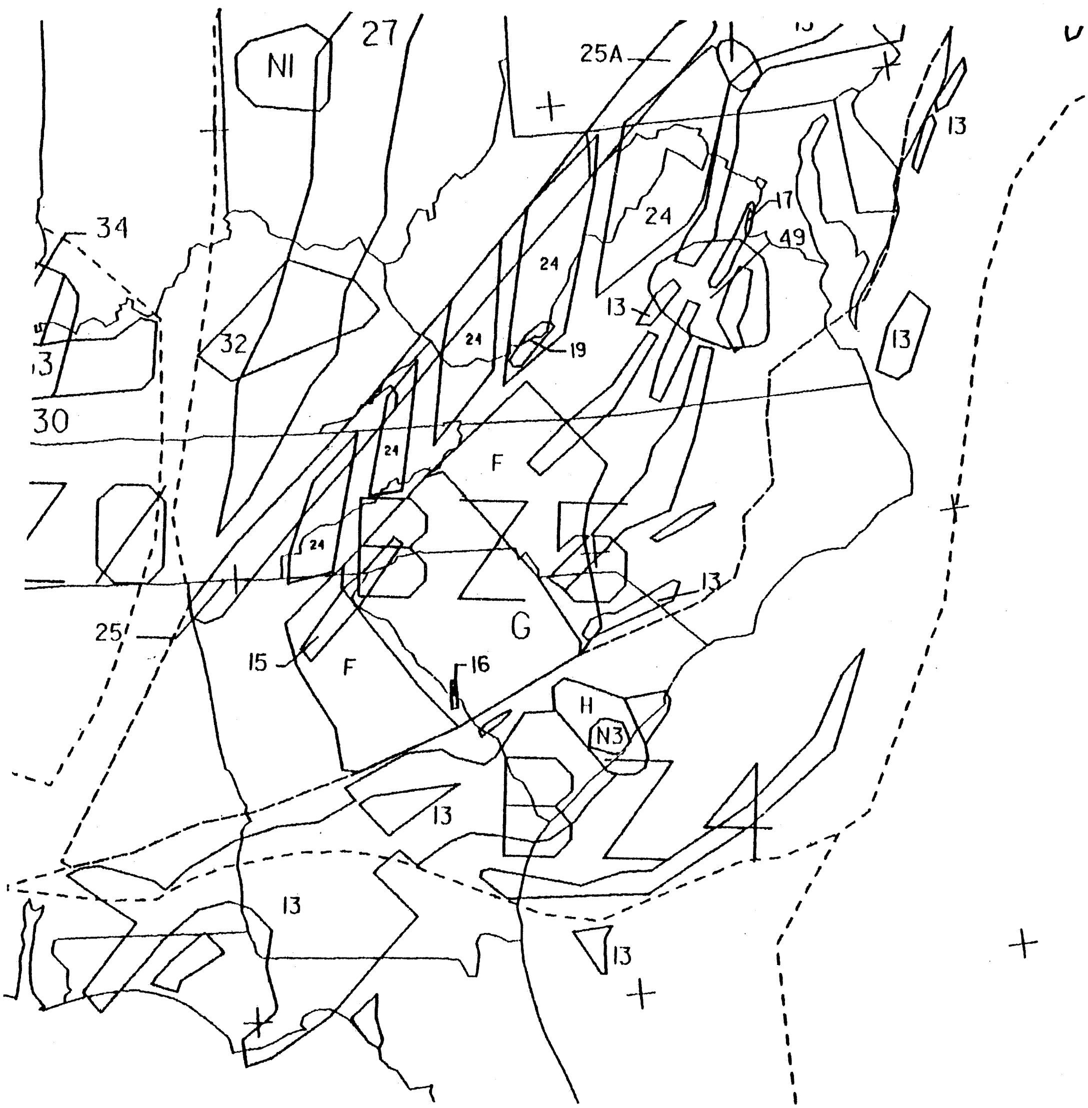


Fig. 4. Seismic sources in Eastern U.S., team II (EPRI, 1986).

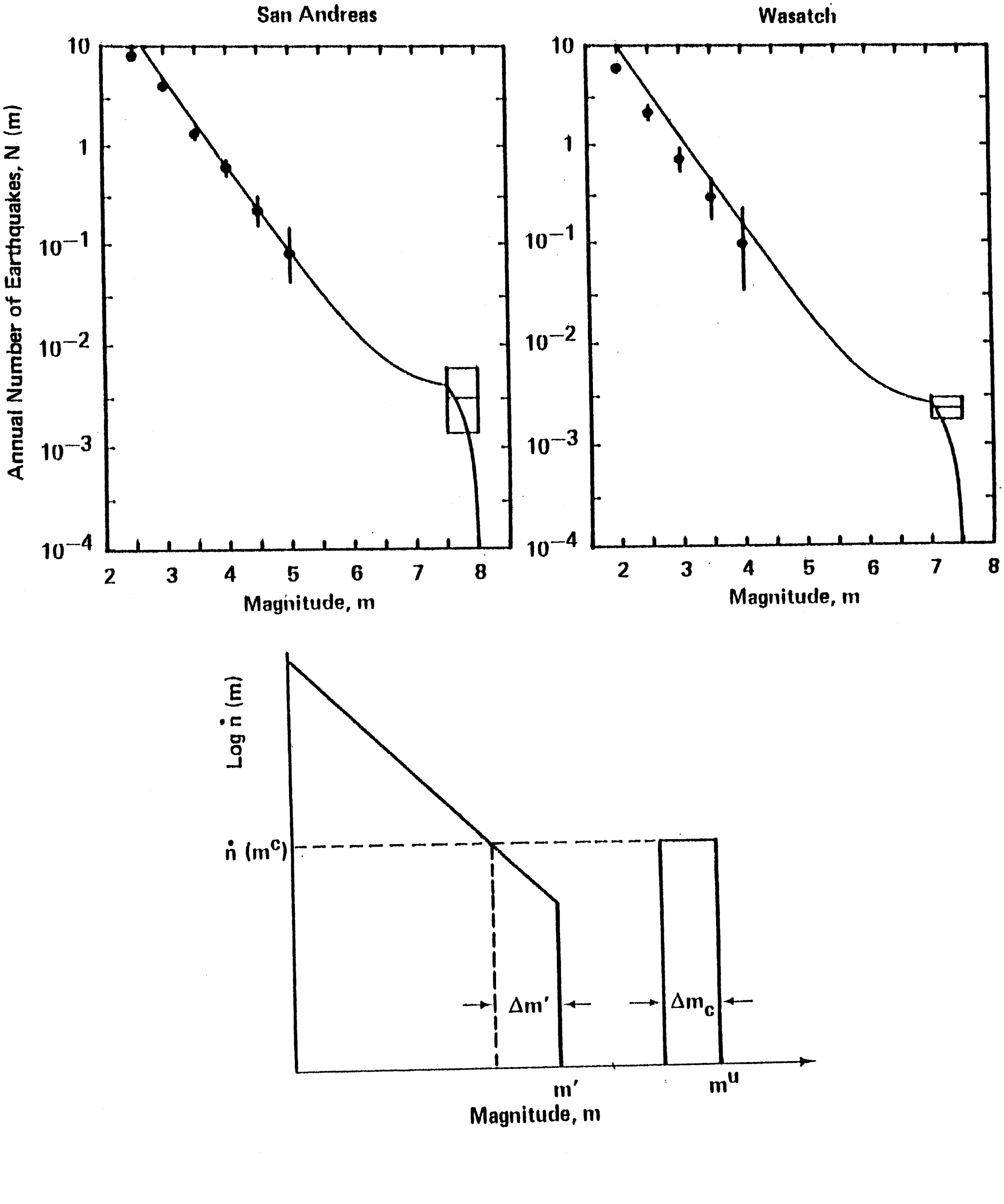


Fig. 5. Characteristic earthquake model (Youngs and Coppersmith, 1985).

For each seismic source (fault or area) the earthquake occurrence model must be specified. Historically it has been customary in seismic hazard analysis to designate simply a magnitude distribution, *e.g.* the exponential distribution of equation 1, and a rate of occurrence per unit time. A simple addition is to recognize that large earthquakes often occur at a rate that is larger than would be predicted by the smaller events, so a «characteristic» earthquake distribution is added to the exponential to represent these larger events. Figure 5 illustrates how this model works in general and for two faults in the U.S. The use of a simple rate of occurrence for earthquakes is appropriate when the frequency of occurrence is low and we are interested in small probabilities of occurrence (*e.g.* 10^{-3} per year or less). Note that this is *not* equivalent to assuming a Poisson process for earthquakes; the use of a simple rate of occurrence gives hazard results in terms of rates of exceedance, which are accurate (and slightly conservative) estimates of probabilities of exceedance. Time-of-occurrence models that have been used are the Poisson, the time-predictable, the slip-predictable, and renewal models.

The last type, renewal models, has been used with success on an on-going basis in California for estimating probabilities of occurrence of large earthquakes in the next thirty years. The use of memory models of this type allows for the time since the last event and recognizes that the stress accumulation and release process on faults is cyclical. Small earthquakes are treated with an exponential magnitude model, but the larger events on each fault, those that release most of the crustal stress on the fault, are treated with the more sophisticated models. Figure 6a) illustrates the probability of occurrence distribution in time and the renormalization of this distribution to account for no earthquake having occurred yet in the earthquake cycle. The effect on the probability of occurrence depends on the dispersion of the initial (marginal) distribution of time of occurrence, as illustrated in fig. 6b). Smaller dispersion in the time distribution results in a sharper increase in hazard as the average time between events approaches. This methodology has been applied in California, for example to faults in the San Francisco Bay area, fig. 7, using times since the last event on each fault and analogies with other regions of the world. Table I shows results of this application in terms of mean recurrence time T, uncertainty σ_T, and estimated probability of occurrence in the next

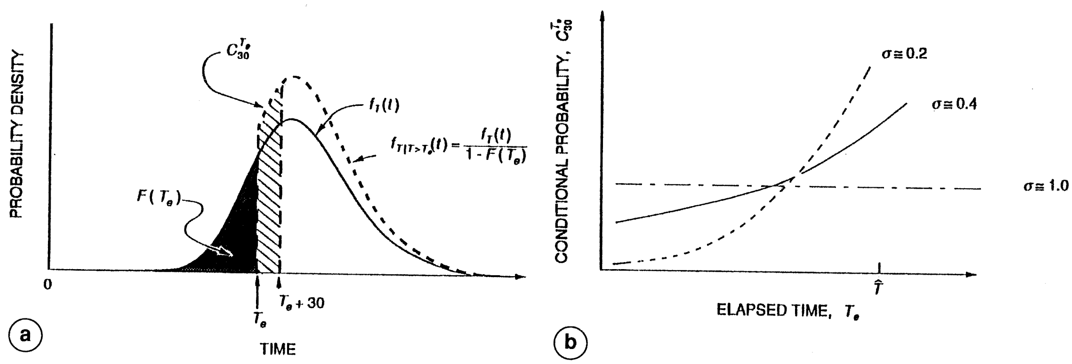


Fig. 6. Probability distribution for time of occurrence (a) and conditional probability of occurrence (b) for renewal model (WGCEP, 1990). a) Graphical interpretation of $C_{30}^{T_e}$, the conditional probability of $T_e \leq T \leq T_e + 30$ given $T > T_e$. See text for explanation of variables. b) Conditional probability, $C_{30}^{T_e}$, of an earthquake in the next 30 years given an elapsed time of T_e since the last event, for several value of σ, the degree of dispersion in the recurrence-time distribution (assumption: recurrence interval, $\hat{T}$, is much greater than 30 years).

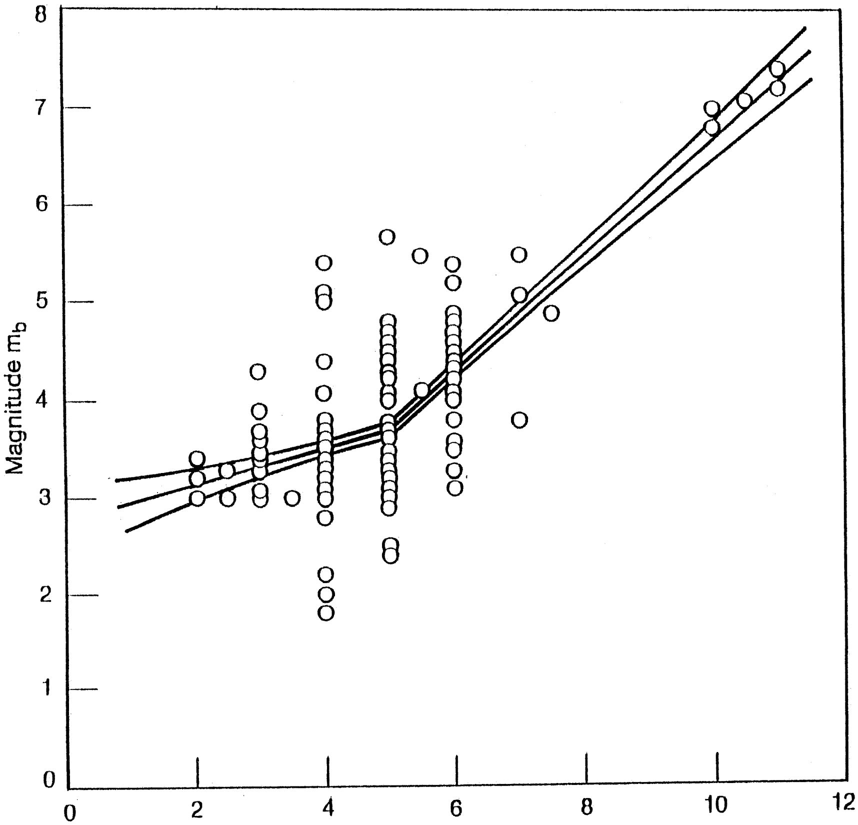


Fig. 7. Example of uncertainty in magnitudes resulting from MMI conversion in Eastern U.S.

thirty years. Such results can be incorporated directly into standard seismic hazard analyses using the probabilities in table I (divided by 30 to translate them to an annual basis), illustrating why the use of a mean rate of occurrence (in this case, over 30 years) in seismic hazard analysis is not equivalent to the assumption of a Poisson process.

For the more general application, particularly where areal sources are used, the exponential magnitude model and average rate of occurrence are adequate to specify seismicity. This follows because earthquakes in specific regions have been shown to follow the exponential distribution; characteristic and other more detailed distributions are proposed for specific faults, but the aggregation of events in a region appears exponential. The density function for the exponential distribution is given as:

$$f_M(m) = k\beta \exp^{-\beta(m-m_0)} \tag{1}$$

where β is the Richter b-value times ln(10), m_0 is a lower-bound magnitude of interest to seismic risk decision, and:

$$k = [1 - \exp^{-\beta(m_{max}-m_0)}]^{-1} \tag{2}$$

The complementary cumulative distribution function, which gives the probability that any specific earthquake will exceed magnitude m, is given by:

$$G_M(m) = 1 - k + k\exp(-\beta(m - m_0)) \tag{3}$$

Rates of occurrence and the b-value of the exponential distribution for areal sources must be estimated based on historical occurrences, or must be inferred by analogy from other regions of similar tectonic environment. For example, typical b-values around the world range from 0.7 to 1.1, depending on the magnitude definition being used.

One of the important considerations in estimating rates of occurrence and b-values from historical data are the effects of uncertainty in the estimates. For example, estimating magnitude from the maximum intensity value for pre-instrumental earthquakes often entails uncertainty with a standard deviation of 0.6 magnitude units. Figure 7 illustrates this effect for the Eastern U.S.

This large uncertainty results from the coarse nature of intensity scales (they cannot distinguish small changes in earthquake characteristics) and from errors in observations. The effect of uncertainty in magnitude estimates is best illustrated by example. Table II shows a summary of hypothetical observations of earthquakes for a period of 200 years, where the only size data available are the maximum intensity value I_0. These have been converted to magnitude using the relation:

$$\overline{m} = 0.8 + 0.6\ I_0 \tag{4}$$

with an observed σ_M of 0.6. Table II indicates that 44 earthquakes of I_0 = VII or larger have been observed. Since I_0 = VII represents the magnitude range 4.7 to 5.3, a logical conclusion would be that the annual rate of occurrence of magnitudes above 4.7 is 44/200 = 0.22 per year. However, this would be correct only if the intensity-to-magnitude relationship were deterministic, which it is not. Figure 8

Table I. Probabilities of occurrence of earthquakes in the San Francisco bay area during the period 1990-2020.

Fault segment	Previous event	Expected magnitude	T	Sigma T	Probability
So. Santa Cruz Mt.	1989	7	91	0.31	0.00
San Francisco Penin.	1906	7	136	0.35	0.37
North Coast	1906	8	228	0.36	0.02
So. Hayward	1868	7	167	0.39	.23
No. Hayward	1836	7	167	0.39	.28
Rodgers Creek	1808 (or earlier)	7	>222	0.39	.22

Table II. Hypothetical earthquake observations for 200 years.

I_0	Number of observations	Cumulative no. of observations	Estimated magnitude	Magnitude range
V	270	404	3.8	3.5-4.1
VI	90	134	4.4	4.1-4.7
VII	30	44	5.0	4.7-5.3
VIII	10	14	5.6	5.3-5.9
IX	3	4	6.2	5.9-6.5
X	1	1	6.8	6.5-7.1

indicates the distribution of magnitudes for each intensity level; for each intensity shown, but most importantly for I_0 = V and VI, there are a significant number of magnitudes expected to be above 4.7. The total estimated number is:

I_0 = V	270 events × 0.067	=	18 earthquakes
I_0 = VI	90 events × 0.30	=	27 earthquakes
I_0 = VII	30 events × 0.70	=	21 earthquakes
I_0 = VIII	10 events × ~1.0	=	10 earthquakes
I_0 = IX	3 events × ~1.0	=	3 earthquakes
I_0 = X	1 event × ~1.0	=	1 earthquake
Total			80 earthquakes

which leads to an estimated rate of 80/200 years = 0.4 per year. Thus with realistic estimates of the uncertainty in magnitude assignment, an error of a factor or two could be made in the rate of occurrence. The error is normally not this large because some earthquakes in the record will be instrumentally recorded, and their magnitude uncertainties will be smaller than 0.6.

A simple method to take into account magnitude uncertainties has been devised by Veneziano and Van Dyke (see EPRI, 1986). It is to use, in recurrence rate estimates, a magnitude m* for each earthquake that is:

$$m^* = \overline{m} + 0.5\,\beta\,\sigma_m^2 \tag{5}$$

This accounts both for the effects of uncertainty in magnitude and for the slope of the mag-

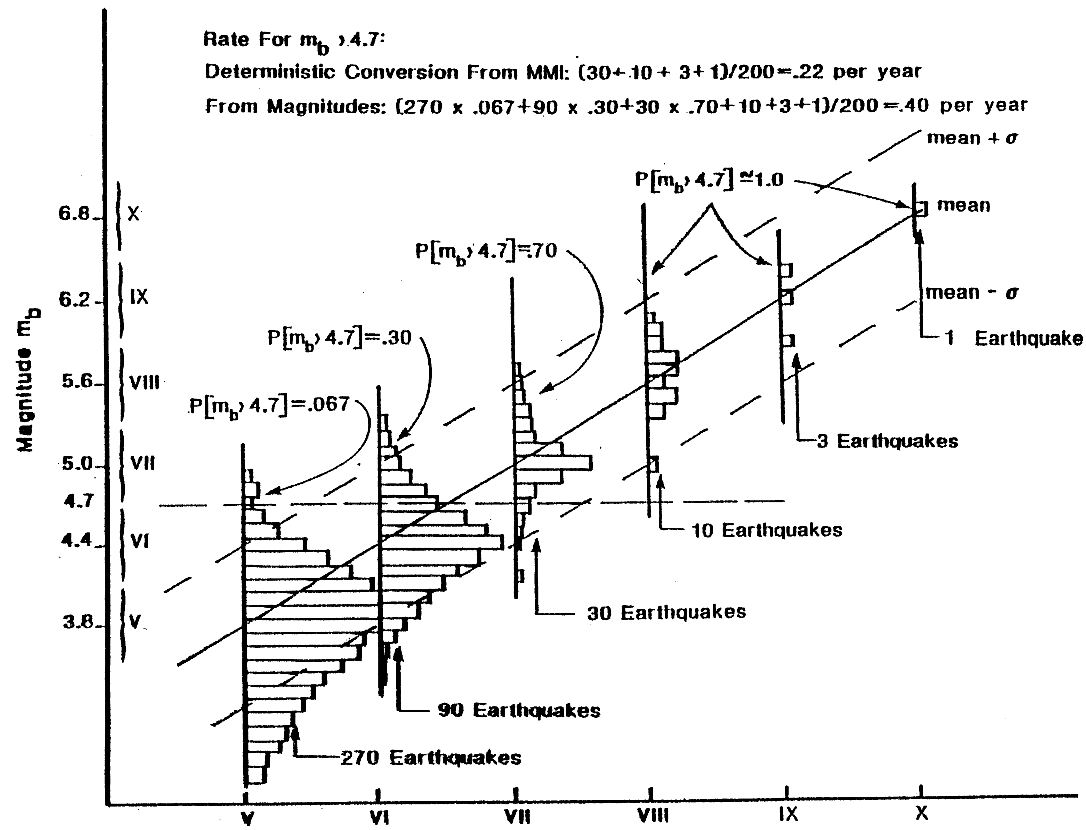
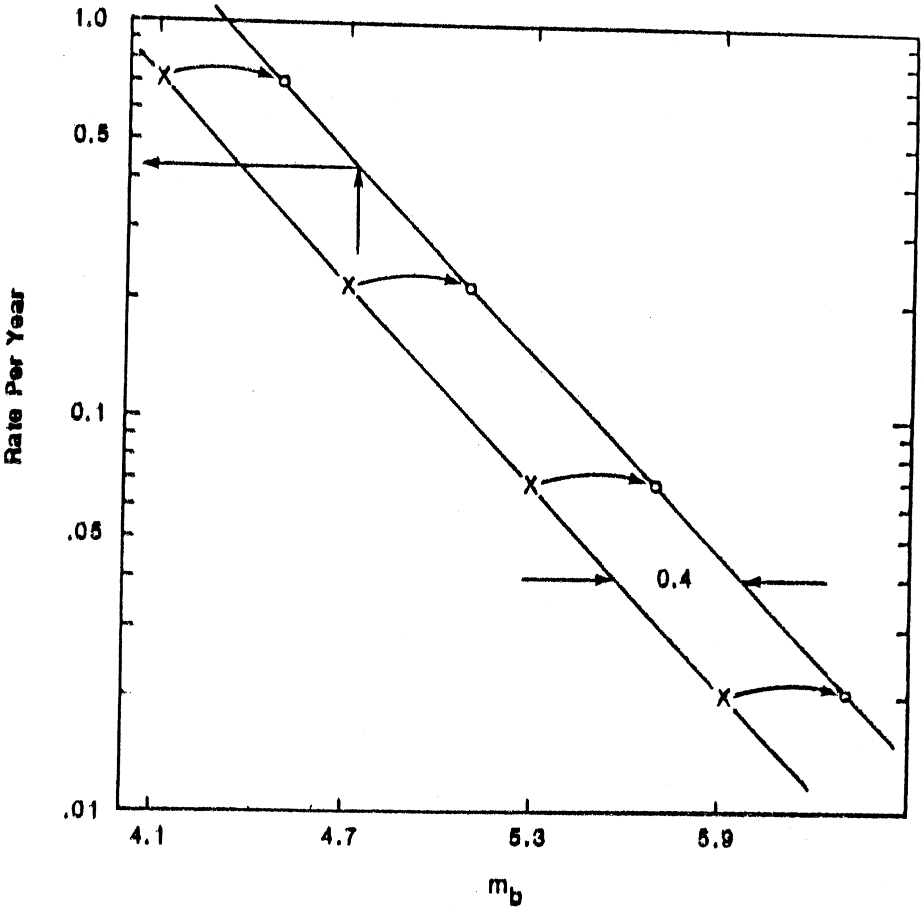


Fig. 8. Distribution of magnitudes for each intensity-example.



$$m_b{*} = \hat{m}_b + 1/2\ \beta\ var(m_b)$$

$$= \hat{m}_b + 0.4$$

Fig. 9. b-value plot showing effect of magnitude uncertainty.

nitude distribution. An illustration of how this simple equation works is shown on fig. 9, which is a standard b-value plot for the hypothetical data of table II. The original data, shown as X's, indicate a rate of occurrence of m > 4.7 of 0.22 per year; shifting the magnitudes by 0.4 (which is calculated by equation 5 as 0.5 × 2.07 × 0.36) leads to the circles and a correct rate of 0.44 events per year.

An additional input parameter is the maximum magnitude for each fault or areal source. A best estimate is often taken to be one-half magnitude unit above the maximum historical magnitude on that fault or in that source, but this estimate has only the weight of precedence. More physically-based estimates are made using functions that relate magnitude to rupture length (for faults) or to the length of tectonic features (for areal sources). Also, analogies of regions with similar tectonic history (*e.g.* intra-plate regions with failed rifts where the current crustal stresses are extensional) can give insight on the largest possible magnitudes.

A final input required is a designation of a ground motion estimation equation. This equation must have a magnitude measure that is consistent with the magnitudes used to specify the activity rate in the seismic sources, and must have a distance definition consistent with the use of faults or areas as seismic sources. To make the latter point clear, if faults are used and ruptures are designated explicitly to represent the source of energy release, the ground motion equation should correctly calculate the closest distance from the rupture to the site or the distance from the center of energy release to the site. If areal sources are used, meaning that earthquakes are represented as point sources, the ground motion equation must correctly use the distance from the point source to the site (including the depth of energy release, *i.e.* the hypocentral distance). It should be evident that the same equation is not appropriate for both applications. Depending on how the ground motion equation is derived, it will be appropriate for one or the other.

The choice of ground motion parameter should be consistent with how the seismic hazard analysis is to be used. Usual parameters of interest are peak ground acceleration (PGA), peak ground velocity (PGV), and spectral velocity (SV) for a specified damping and structural frequency (often between 1 and 25 Hz). For horizontal components the usual procedure is to estimate the amplitudes for a random horizontal component, rather than the larger of two orthogonal components placed at random azimuths. The difference between the two is about 15% to 20%.

In cases where the primary record of earthquakes consists of pre-instrumental events for which maximum intensity levels I_0 have been assigned, one should consider how best to estimate ground quantitative levels of ground motion. The

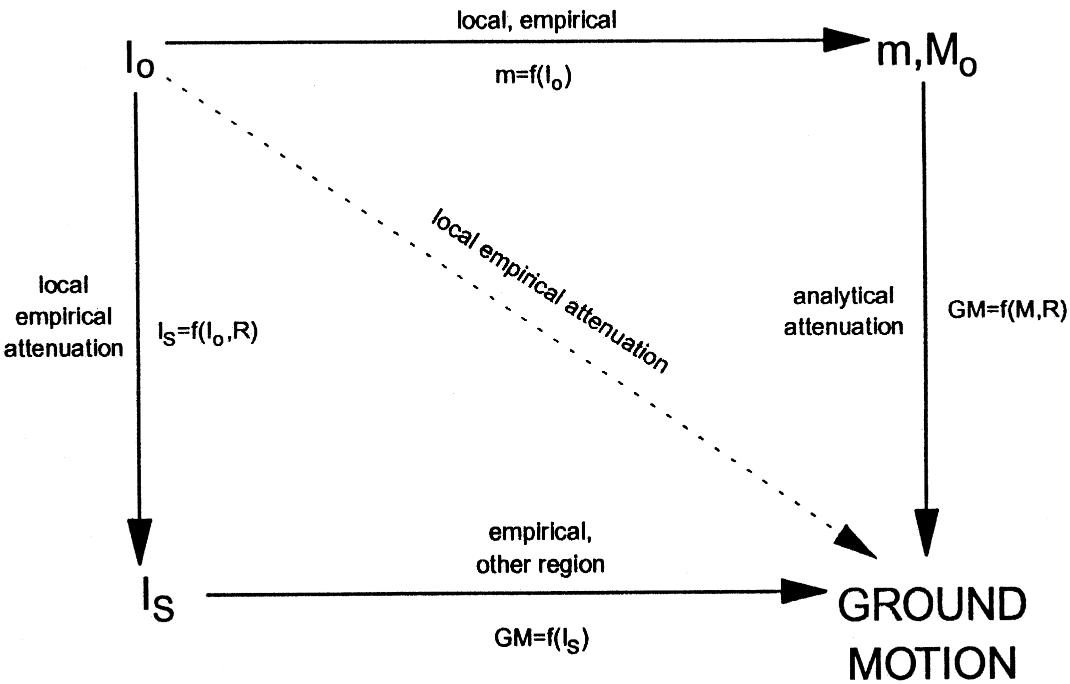


Fig. 10. Conceptual methods of estimating ground motion from I_o.

alternatives are shown in fig. 10. Starting with a value of I_0 in the upper left, one wishes to make an estimate of ground motion in the lower right. The most straightforward method, involving the fewest assumptions, is to use a local empirical attenuation equation, the diagonal, dashed line in the figure.

However, this is rarely possible because a significant number of strong motion records are usually not available for a region where most of the earthquake history is pre-instrumental (few earthquakes have occurred in modern times).

An alternative is to use a local empirical attenuation to estimate site intensity I_s (at the bottom left) and adopt empirical relations to estimate ground motion as a function of I_s (and perhaps magnitude M and distance R). This has the disadvantage that known differences, for example in the ground motion frequency content, cannot be incorporated directly.

The preferred method is to estimate magnitude from I_0 (at the top of the figure) and use an analytical attenuation to predict ground motion from M and R. This analytical equation *can* incorporate known characteristics of local earthquake motions.

An important quantity associated with the ground motion equation is the residual variability in observations given the prediction. Usually these observations are assigned a lognormal distribution, with $\sigma_{\ln(\text{ground motion})}$ equal to 0.35 to 0.6. The specific value will depend on how many conditions are treated in the ground motion equation; an analysis made with all strong motion records will show a larger variability than one derived only from free-field sites, or one derived only from records obtained in the basements of large structures. The appropriate variability will depend on how the near-surface soil or rock response is treated; if it is handled as an uncertainty, with alternate ground motion equations, the residual variability will be smaller than if the near-surface response is treated as variability among similar sites. Also, the variability assigned to ground motion equation based on point source calculations should logically be larger than the variability assigned to rupture distance calculations; in the latter case more is known about the geometry of the energy release relative to the site, so the residual uncertainty should be lower.

3. Seismic hazard calculations

Methods of seismic hazard calculations fall into two categories. The first consists of historic methods, which are based on historical earthquake occurrence and which do not use interpretations of faults, seismic sources, or seismicity parameters. The second are called «deductive methods», because interpretations are made to deduce the causes of earthquakes (faults and areal sources) and their characteristics (the seismicity parameters).

An outline of the steps in the non-parametric *historic* method is shown in fig. 11. In the top left, the earthquake catalog in the vicinity of the site is plotted. In the top right, a ground motion function is adopted that predicts ground motion intensity (in quantitative terms such as PGA) as a function of I_0 or M. For each historic earthquake, using its value of M (or I_0) and R, the distribution of ground motion is estimated, as shown in the bottom right. This gives the historical rate at which different levels of ground motion are exceeded. Finally, this function is divided by the number of years of the catalog to obtain an annual rate of exceedance, which for small values is a good approximation to the annual probability of exceedance (illustrated in the bottom left of fig. 11). This method has the advantage that seismic sources and seismicity parameters are not needed, so it involves fewer interpretations than the deductive method.

Its primary disadvantage is its unreliability at lower annual probabilities than the inverse period of the catalog. This reliability can be extended somewhat by fitting a distribuction to the tail (in which case the method is called the «parametric historic method»), but this does not relieve concerns that issues such as seismic gaps and uncertainties in tectonics have been neglected.

Practical applications of the historic method are more complicated than portrayed by fig. 11 because, for example, earthquake catalogs typically are complete for different time periods at different magnitude levels.

Details of the historic method are available in Veneziano *et al.* (1984).

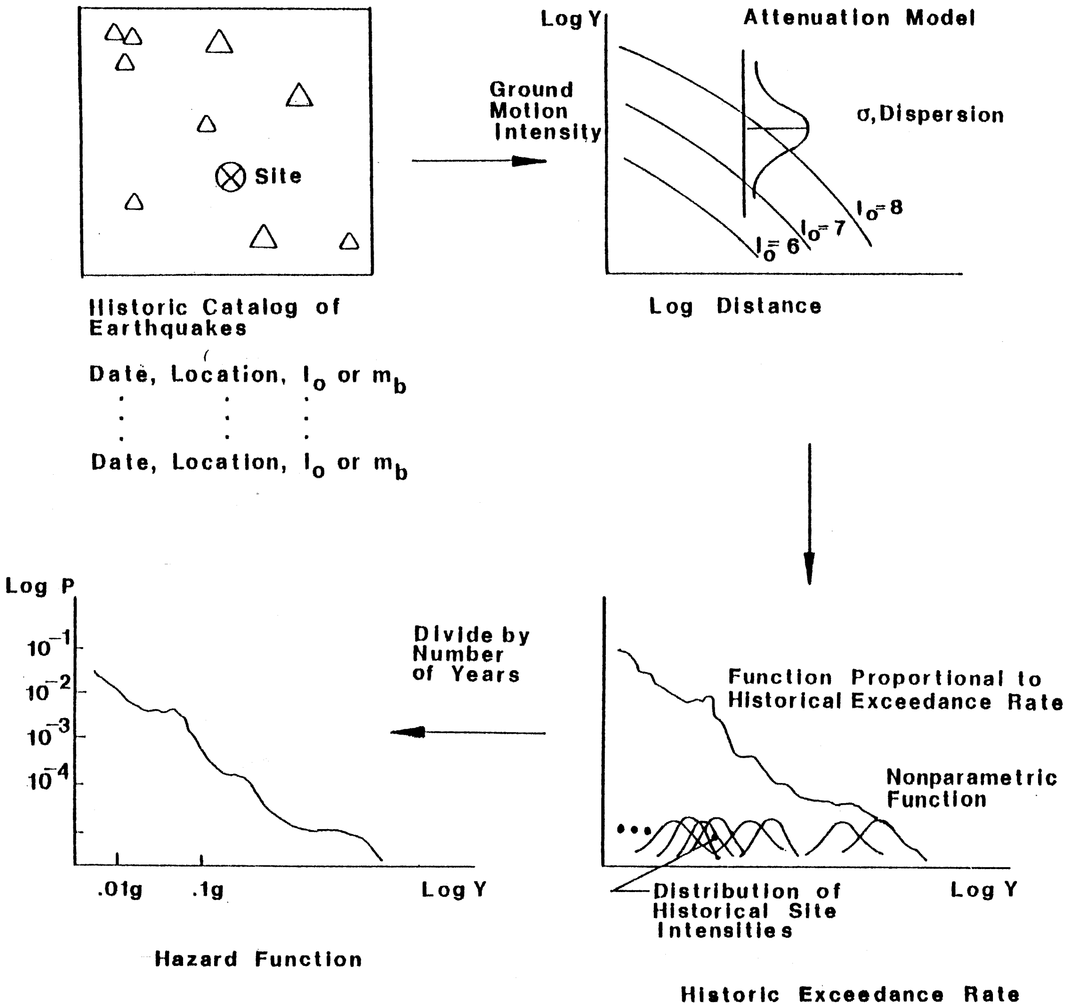


Fig. 11. Steps in non-parametric historic hazard method (Veneziano *et al.*, 1984).

The steps involved in the *deductive* method are illustrated in fig. 12. In step A, seismic sources (including faults) are defined; this allows calculation of a distance distribution $f_R(r|m)$. In step B, seismicity parameters are defined, for example the minimum magnitude m_0, the maximum magnitude m_{max}, the annual rate of earthquakes above m_0, and the magnitude distribution $f_M(m)$. In step C, the ground motion equation is selected, giving the complementary cumulative distribution function $G_{Am,r}(a^*)$ for any ground motion amplitude a^*. Step D is the integration of the distributions from steps A through C using an application of the total probability theorem to obtain the probability per unit time that ground motion amplitude a^* is exceeded:

$$P[A>a^* \text{ in time } t]/t =$$

$$= \sum_i \mathrm{v}_i \int\int G_{A|m,r}(a^*)\, f_M(\mathrm{m})\, f_R(r|m)\, dmdr \quad (6)$$

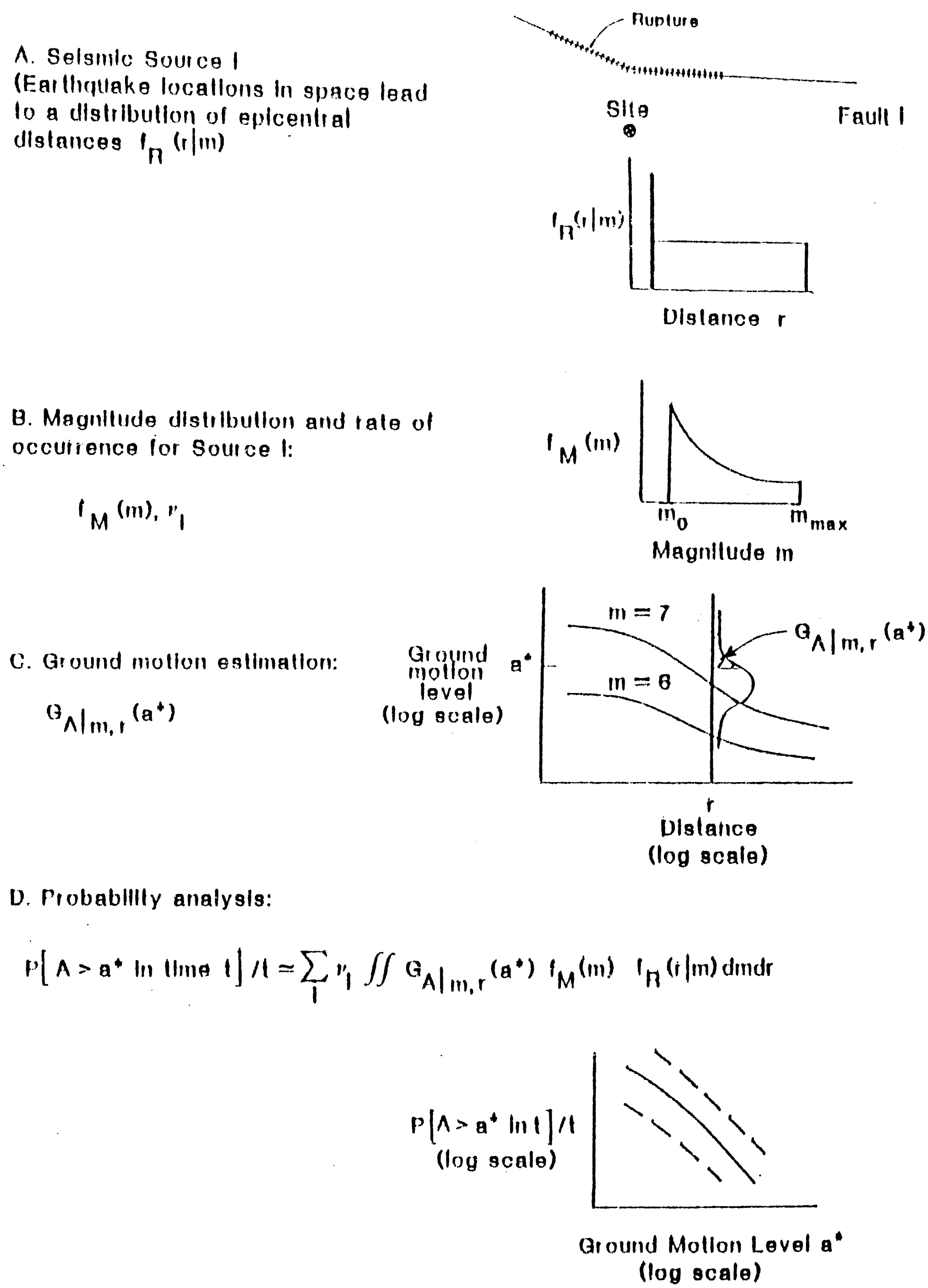


Fig. 12. Steps involved in deductive method of seismic hazard analysis.

This is called the *deductive* method of seismic hazard analysis because we deduce what are the causative sources, characteristics, and ground motions for future earthquakes. This method was first published by Cornell (1968), with many applications since. This method is preferred over the historic method for low probabilities, because it can account for hypotheses such as migration of seismicity, seismic gaps, cyclical strain release, and non-stationary seismicity that may not be captured by historic methods. However, the two procedures are complementary; the historic method gives a realistic baseline for high probabilities (short return periods) and thereby is a good check for the deductive method at those probabilities.

4. Treatment of variability

Variability in seismic hazard analysis is important to treat in a logical way so that the hazard results can be used appropriately. Two types of variability are defined as:

– randomness, or aleatory variability, is inherent in natural processes and cannot be reduced by additional data collection or better modeling. It includes details of the earthquake rupture process that lead to pulses in ground motion records, the reinforcement of different wave types arriving from different paths to the same site at the same time, the magnitude of the next earthquake in a defined seismic source, and similar phenomena;

– uncertainty, or epistemic variability, results from statistical or modeling variations and could, in concept, be reduced with additional data or better modeling. Examples include alternative hypotheses on active seismic sources in a region, the maximum magnitude possible on a specific fault, or the correct median ground motion equation for a region.

These variabilities are treated differently. The seismic hazard analysis, whether by the historic or deductive method, integrates over randomness to calculate the seismic hazard curve; this is what is meant by «annual probability of exceedance», *i.e.* the probability represents randomness. Uncertainties are treated by multiple hypotheses and distributions of hazard curves. Uncertainties are expressed as a confidence level for the hazard results, *e.g.* «I am 85% confident that the 500-year PGA is less than 0.3g». Two ways to treat uncertainties in input assumptions are with logic trees and with Monte Carlo analysis. Both methods explicitly represent uncertainties in hypotheses and are useful organizational and documentation tools for these uncertainties. Table III compares the advantages of logic tree and Monte Carlo analysis for quantifying uncertainties in seismic hazard.

As an example of a logic tree formulation, the left side of fig. 13 illustrates a simple logic tree involving uncertainties in geological in-

Table III. Quantitative treatment of uncertainties.

Method	Advantages	Disadvantages
Logic tree	Explicitly alternatives Direct choice, few parameters Correct mean is calculated Easy to specify dependencies Sensitivity studies are easy	Large numbers of calculations No continuous distributions
Monte Carlo	Allows continuous and discrete distributions Number of calculations can be controlled	Ill-constrained mean More difficult to specify dependencies Sensitivity studies can be inefficient

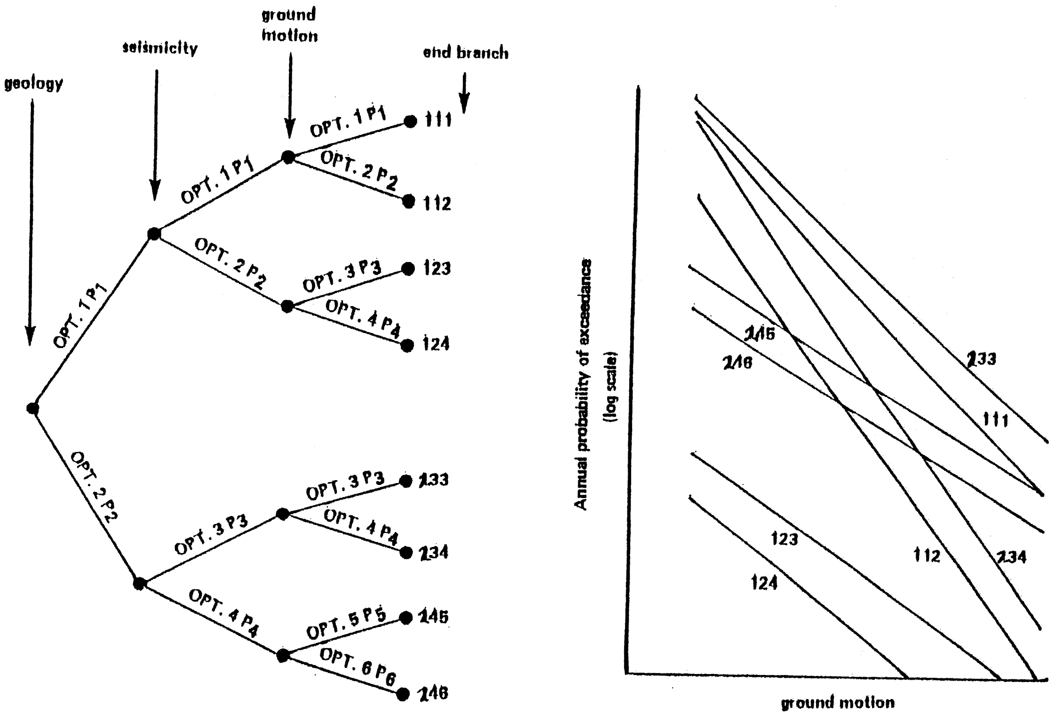


Fig. 13. Example of logic tree application to derive multiple hazard curves.

terpretations, seismicity assumptions, and ground motion models. Each uncertain model or parameter is represented by a node, and branches emanating from each node represent discrete alternatives on that model or parameter value. In the example of fig. 13, each node has two branches, so there are eight end branches, each representing a set of assumptions for which seismic hazard calculations can be made (this would apply both for the historic and deductive methods). Once the hazard calculations are completed for the assumptions represented by each end branch, the hazard curves can be plotted as illustrated on the right side of fig. 13. These curves represent the uncertainty in seismic hazard as derived from uncertainties in the inputs.

Segregating seismic hazard variability into two types is important because the seismic hazard estimates will evolve with time as we learn more about seismicity, tectonics, and strong ground motion estimation. Figure 14 illustrates two sample functions illustrating how the acceleration corresponding to a target probability might change with time. At present we may have a large uncertainty on that acceleration, but our estimate will change (and the residual uncertainty will reduce) in the future. These potential changes can affect our current decisions on seismic design levels or mitigation decisions; one such analysis is given by McGuire (1987).

An example of a seismic hazard analysis with uncertainty is shown in fig. 15. This application was for the Diablo Canyon Power Plant site in coastal California, an area where we probably have as much information as anywhere in the world on tectonics, seismicity characteristics, and strong ground motion estimation. Even with all of this knowledge there

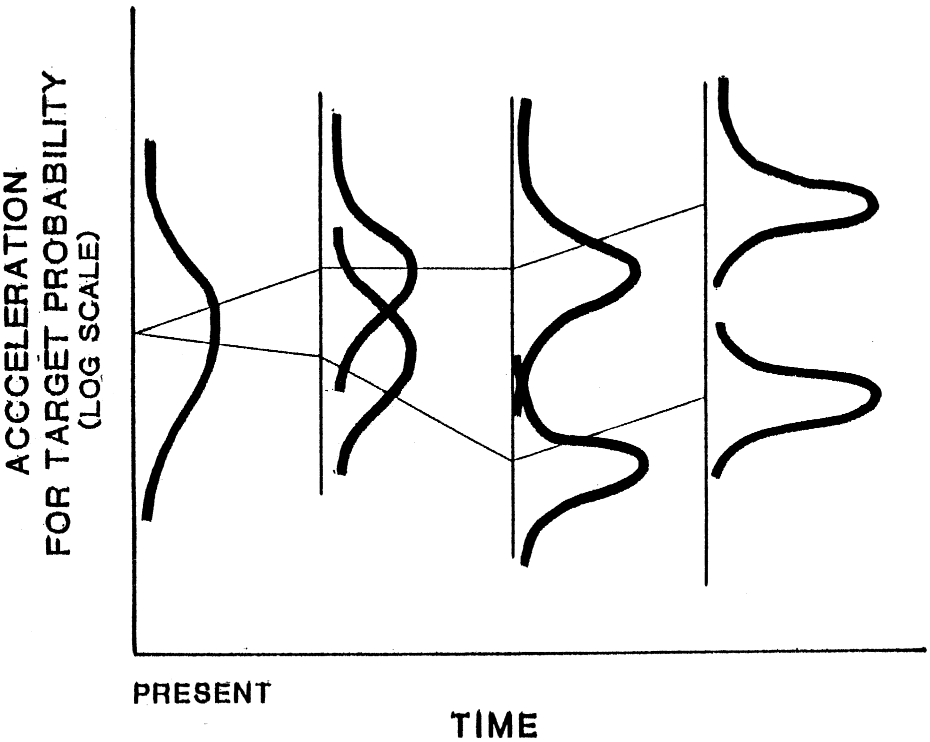


Fig. 14. Two sample functions of design acceleration evolution in time.

is significant uncertainty in the seismic hazard. Figure 15 shows annual probability of exceedance versus spectral acceleration in the frequency range 3 to 8.5 Hz, which was determined to be the most relevant single parameter for representing plant response to earthquakes. At an annual probability of 10^{-3}, the range of ground motion (from the 10th to 90th percentile) is a factor of two. Viewed another way, at a spectral acceleration of 1.5g (corresponding to a peak ground acceleration of 0.6g to 0.75g), the uncertainty in annual probability is two orders of magnitude (from the 10th to 90th percentile). This illustrates the large uncertainties in seismic hazard we have, even in parts of the world where tectonics, seismicity, and ground motion are relatively well-understood. It also illustrates why it is important to make an explicit analysis and statement of uncertainties, so they can be accurately represented.

The large uncertainties in seismic hazard are not a defect of the method. They result from lack of knowledge about earthquake causes, characteristics, and ground motions. The seismic hazard only reports the effects of these uncertainties, it does not create or expand them. Other methods, in particular deterministic methods, are inferior if they do not recognize and treat the inherent uncertainties in assumptions. Ignoring these uncertainties means that decisions regarding earthquake mitigation made using those results will be ill-informed.

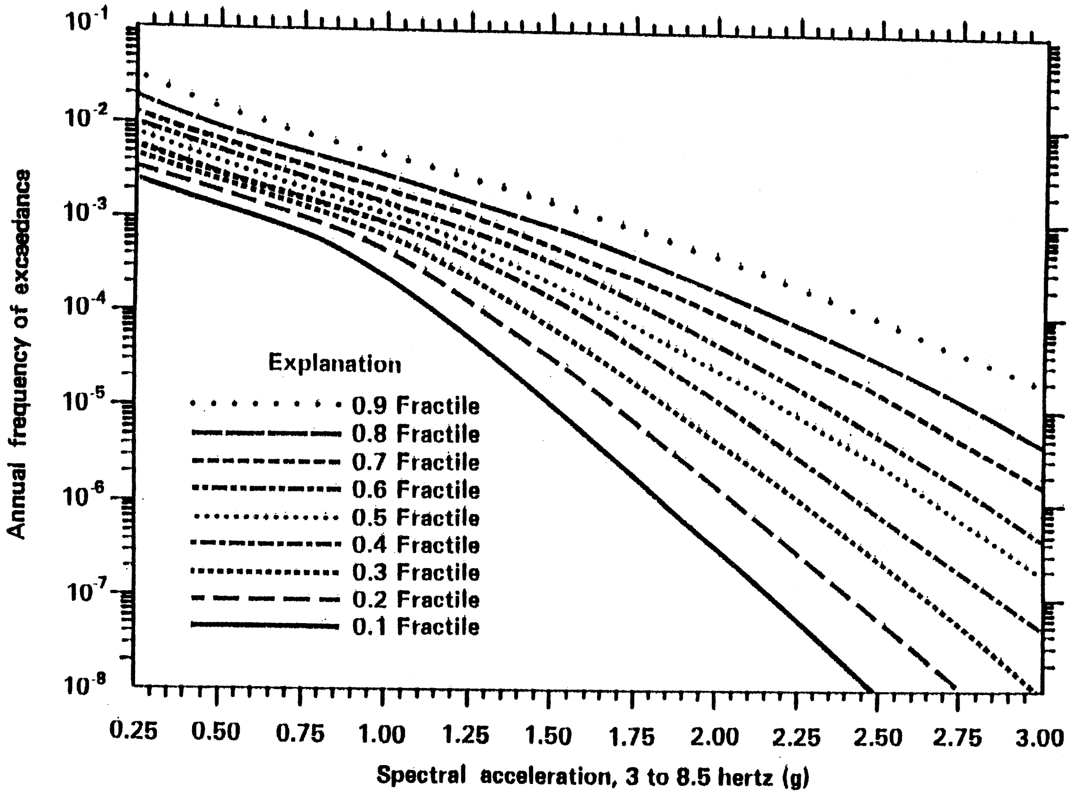


Fig. 15. Example of uncertainties in seismic hazard curves (Pacific Gas and Electric Co., 1988).

5. Summary

Modern methods of seismic hazard analysis allow all information on tectonics, seismicity, and earthquake ground motions to be incorporated into the analysis. Alternative interpretations can be accommodated through a quantitative evaluation of uncertainties, expressing uncertainties in seismic hazard as a function of uncertainties in the inputs. Seismic hazard should be conduced with quantitative measures of ground motion, *e.g.* peak acceleration, peak velocity, or response spectrum amplitudes. The use of qualitative intensity measures (*e.g.* the modified Mercalli scale) requires translation into engineering quantities, and that translation involves significant errors and approximations, which should be avoiled.

Calculational methods of seismic hazard can be divided into historic and deductive methods. Historic methods, particularly non-parametric applications, are useful for annual probabilities that are the inverse of the length of the earthquake history in the region, typically 10^{-1} to 10^{-2} per year for most parts of the world. Deductive methods are more reliable for smaller probabilities (10^{-2} to 10^{-4} annual probability and lower) but should match the results of historic methods at the smaller probabilities (or there must be a good physical explanation of the difference).

Whether historic or deductive methods are used, the range of hazard should be represented. This should include, as a minimum, several fractiles such as the 15th, 50th, and 85th, plus the mean hazard. This allows earthquake loss mitigation decisions to take into account uncertainties in whatever manner is appropriate for that decision process. If a single result is required, *e.g.* for the mapping of seismic hazard at a chosen return period, the *mean* hazard should be selected. This follows for two reasons. First, in the decision-theoretic sense, the mean hazard allows target safety goals to be met, on average, over all sites. For example:

if X = earthquake loss in city 1,
Y = earthquake loss in city 2, and
Z = total loss = X + Y,

then $\overline{Z}r = \overline{X}r + \overline{Y}r$

but $\hat{Z} \neq \hat{X} + \hat{Y}$.

Second, the mean is sensitive to all interpretations, particularly extreme ones that lead to high hazard with low likelihood, and thus represents a composite of all hazards. This is not true of the median.

Probabilistic seismic hazard calculations are well established in the theoretical sense. The real effort should go into obtaining and quantifying the appropriate inputs to the analysis, so the results will reflect current knowledge of the earthquake characteristics in the region. This is the challenge for the seismic hazard analyst.

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