An Introduction to Probabilistic Seismic Hazard Analysis

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Abstract

Earthquakes and their accompanying natural hazards (e.g., ground shaking, ground failure, surface faulting, tectonic deformation, inundation) pose a widespread threat to human activities and to man-made structures and facilities. Seismic hazard analysis, the quantitative estimation of the hazard of earthquake ground shaking at a site, provides valuable guidance for informed decision-making on mitigating the earthquake threat. Recent methodological advances in seismic hazard analysis allow marked improvements in incorporating fundamental input from geology, seismology, and earthquake engineering into the analysis in an orderly way.

Rigorous estimations of seismic hazard (and of corresponding "risk" of social or economic consequences) require carefully prescribed models of the space, time, and size distribution of earthquakes, together with models of ground-motion attenuation with distance. Given these inputs, up-to-date probabilistic methods may be applied to compute the level of groundshaking hazard, expressed as the probability of not exceeding some particular level of ground motion at one or more sites during a time period of interest. Importantly, the probabilistic approaches provide a well-founded basis for representing natural variability, and they allow the treatment of uncertainties arising from incomplete knowledge. To interpret correctly the results of a probabilistic seismic hazard analysis, it is necessary to understand underlying assumptions and the basic concepts of probability.

Introduction

Earthquakes pose a widespread threat to human activities and to man-made structures and facilities. The threat primarily arises from natural hazards that accompany earthquakes, notably ground shaking, ground failure, surface faulting, tectonic deformation, and inundation. The purpose of this paper is to present a tutorial introduction, together with an overview of state-of-the-art approaches, to seismic hazard analysis (SHA). Despite its seemingly general meaning, SHA has come to have a specific engineering connotation—namely, the quantitative estimation of the hazard of earthquake ground shaking (ground motion) at a site. This is the sense with which we use the term throughout this paper. Figure 1 provides a conceptual guide.

The phenomenon of ground shaking is the most widespread and damaging earthquake-related hazard. Its characterization at one or more sites during any future period of time is of fundamental importance, not only for defensive engineering design, but also as a basis for evaluating "risk," i.e., the likelihood that social or economic consequences will be suffered. SHA is relevant to a broad spectrum of professionals. Our intended audience for this tutorial includes earth scientists who would typically be called upon to provide input for an SHA and any decision maker (earth scientist or other) who needs to understand not only the underlying assumptions and methodology of an SHA but also the correct interpretation of its results.

The specific focus of SHA upon the hazard of ground shaking does not diminish the importance of other earthquake-related hazards. Rather, it recognizes that the other hazards are localized and can be studied and delineated by direct geological observations (e.g., Ziony and Yerkes, 1985). For a more complete description of the various hazards associated with earthquakes, we refer the reader to Hays (1981) and Blair and Spangle (1979) for nontechnical explanations, and to Ziony (1985) for an excellent, comprehensive case study of earthquake hazards in southern California. The evaluation of any earthquake hazard basically involves an assessment of the location,

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Distribution in Space

Earthquakes naturally do not occur uniformly throughout an areal source or on a fault in a given time period. The modeled spatial distributions should reflect the relative likelihood of occurrence in the future, much as a probability of one-half reflects the likelihood that a flipped coin will land heads-up. For an areal source the common assumption is that earthquakes occur randomly in space throughout the source and that the occurrence rate within the source is constant (i.e., spatially homogeneous). Recent innovations allow the seismicity parameters a and b that we described earlier to vary spatially within a source (EPRI, 1988). One might choose, for example, to mimic historical seismicity patterns. Advances in paleoseismology and fault mechanics now allow, for some well-studied faults, detailed specification of the location and extent of rupture for future surface-faulting earthquakes (see Crone and Omdahl, 1987).

Size Distribution

Earlier we emphasized that earthquake magnitude is the fundamental measure of size for a PSHA, and we described the Gutenberg-Richter relation for frequency of occurrence versus magnitude. Some additional comment on earthquake size is warranted. Conventional magnitude scales measure earthquake size based on the peak amplitude of seismic waves in a limited band of period or frequency (Kanamori, 1983). For example, Richter or local magnitude, M_L, and body-wave magnitude, m_b, both are common measures of short-period ground motion coincidentally of particular engineering interest. The conventional scales "saturate" (i.e., reach a limiting value) for large earthquakes when the fault rupture length greatly exceeds the wavelength of the seismic waves to which a particular scale is keyed. A more uniform and physically meaningful measure of the strength of an earthquake source, particularly in terms of fault slip and rupture dimension, is seismic moment, M_o, which can be converted into a "moment magnitude," $M_w [M_w = (\log M_o - 16.1)/1.5]$ (Kanamori, 1983). These concepts become important when considering the maximum-size earthquake that must be specified for each source zone (see Coppersmith et al., 1987, regarding approaches to estimating the maximum earthquake).

Although the Gutenberg-Richter relation may adequately describe the magnitude distribution for a region, growing evidence suggests that it may not do so for individual faults. One distribution preferred for some major faults is the "characteristic" magnitude model (Wesnousky et al., 1983, and Youngs and Coppersmith, 1985). One form of this model uses an exponential form as its basis, but adds a large mass of probability at the high end (near the "characteristic" earthquake) to account for the belief that earthquakes of a certain large size occur more frequently than simple extrapolation from smaller magnitudes would predict. These kinds of models have been proposed for the San Andreas fault in California, for the Wasatch fault in Utah, for intraplate faults in Japan, and for subduction zones. Other magnitude distributions have been proposed in the literature (e.g., nonlinear exponential forms, extreme-value distributions, and others; see Anagnos and Kiremidjian, 1988), but they are not generally used in PSHA because they have not received wide recognition as being more appropriate than the Gutenberg-Richter relation, and their use generally has only a small effect on the calculated hazard.

Earthquake-recurrence parameters for a fault-specific source can be derived, with certain assumptions, if the long-term slip rate on the fault or fault segment is known from tectonic or paleoseismologic studies (Schwartz and Coppersmith, 1986, give an overview). In some areas where historical seismicity is inadequately documented or absent, such an approach may be the only one available for characterizing earthquake recurrence on the fault source. Elsewhere, the approach allows useful comparison with seismicity parameters computed from earthquake catalogs. We elaborate on the use of fault slip rates for hazard analysis in the Current Issues in PSHA section.

Time Distribution

The probability analysis that we are interested in, summarily described by the equation in Figure 5d, contains an important term, ν_i, that relates to the *time* distribution of earthquakes. For a given source i, ν_i is the mean rate of occurrence—or, equivalently, the expected number—of future earthquakes of $m_o < m \leq m_{max}$ per time period t. This expected number can be calculated from *any* earthquake time distribution, or from an earthquake prediction. For earthquake main shocks in a region (i.e., excluding dependent events such as foreshocks and aftershocks), the most common assumption is that successive earthquakes are random in time and follow a Poisson process. For this reason, the Poisson process is often considered a "standard assumption" of a PSHA, but it is by no means a requirement. The only restriction is that the term ν_i represent the expected rate of occurrence for *whatever* underlying time distribution is used.

In a Poisson process, the events of a sequence occur with no "memory" of the time, size, or location of preceding events, their interarrival times are exponentially in which an instrument might be located (i.e., the type and size of building and instrument location within the building). These factors mean that some care needs to be applied in selecting records for an empirical analysis and in conducting the analysis itself. Campbell (1985) presents a good summary of issues related to deriving empirical ground motion equations for PSHA.

Equations Based on Theory

In recent years ground-motion equations based on theories of wave generation and transmission have gained acceptance for PSHA. Notable among these is the band-limited, white-noise model of ground motion, which accurately predicts all measures of shaking (peak parameters as well as response spectra) as a function of the moment and stress drop of the earthquake (Hanks and McGuire, 1981; Boore, 1983; McGuire et al., 1984). These methods have become popular as the number of strong-ground-motion records has increased, providing a substantial data set to calibrate and verify these theoretical models. They have some advantage over empirical methods in that physical arguments can be used to predict the character of ground shaking where few data have been recorded. However, the predictions must still be regarded as extrapolations of the theory beyond where it has been validated, until confirmatory records are obtained.

Variability in Ground Motion

An important influence on seismic hazard is the variability in ground motion, that is, the scatter in amplitudes around the best estimate for a given magnitude and distance. This scatter is observed in all strong-motion data sets, even when records have been normalized to the same magnitude, distance, and recording site conditions.

Causes of variability are randomness in earthquake properties from event to event, and uncertainty in properties of the transmission path and site conditions. Regarding randomness, no two earthquakes are identical in terms of the rupture dynamics and the interference and scattering of waves along the transmission path, even if the same magnitude earthquake reoccurs on a section of an active fault. For all earthquake records, there is uncertainty about the exact influence of crustal properties along the transmission path, and about the near-surface soil or rock properties and their effects on ground-motion energy. Therefore, we treat different sites and recording paths as the same, even though they have different effects on the recorded ground motion. All of these factors result in significant scatter in ground-motion amplitudes.

This scatter is usually quantified by the standard deviation of the logarithm of ground motion. Values (using natural logarithms) in the range 0.4 to 0.5 are usually reported for empirical studies where a significant effort has been made to categorize the recording-site conditions accurately, and where distance to the fault rupture surface is used as the distance measure. Early studies reported larger scatter, usually because site conditions were not accounted for or known with certainty and because a less meaningful measure of distance was used. A standard deviation of 0.4 to 0.5 for the natural logarithm of a ground-motion parameter implies a coefficient of variation (the standard deviation divided by the mean) of a factor of 1.50 to 1.65. This significant variability fundamentally affects the level of the calculated hazard.

Calculation of Seismic Hazard

In its simplest expressions, seismic hazard is represented by three quantities: an amplitude of ground motion, a time period of interest, and a probability that the amplitude will be exceeded during that time period. Seismic hazard *curves* present a series of such results for different amplitudes, and seismic hazard *maps* present a set of amplitudes at different locations for which the probability and time period are constant.

The seismic hazard calculation is represented by the equation with a double integral in part d of Figure 5. The probability of exceeding a ground-motion amplitude a^* is calculated for one possible earthquake magnitude and location, that result is multiplied by the probability of occurrence of that magnitude at that location, and this process is repeated for all possible magnitudes and locations. In general, these probabilities are calculated on an annual basis, i.e., the time period is one year. (This is not a restrictive assumption; the results can be translated rather easily to other time periods.) Because our usual interest is in low probability events, the total annual probability of exceeding some amplitude a^* is the sum of annual probabilities from all possible earthquakes. This simple method for calculations is the center of all seismic hazard results.

The seismic hazard calculation integrates over all possible earthquakes and produces a composite probability of exceedance which is both a strength and a limitation. On the positive side, all earthquakes are considered and are weighted by their relative probabilities of occurrence; rare, strong earthquakes are considered in the appropriate relationship to frequent, weak earthquakes. On the negative side, a single influential earthquake cannot

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