PROBABILISTIC EVALUATION OF SEISMIC HAZARD FOR SITES LOCATED NEAR ACTIVE FAULTS

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SUMMARY

This paper presents a methodology for probabilistically estimating the seismic hazards associated with facilities located near active faults. The proximity of a fault poses three problems not normally associated with such an analysis: (1) the domination of the hazard by a single fault, (2) the necessity of predicting ground motion in the near-source region of the fault, and (3) the potential for fault rupture beneath the facility. These problems are accommodated through the use of techniques that evaluate strong ground motion, seismicity, and fault rupture from seismotectonic data obtained for the fault of interest.

INTRODUCTION

The seismic design of critical facilities such as nuclear power plants, major dams, and LNG facilities requires the evaluation of seismic hazards associated with potentially active faults located near the facility. Because of the small probabilities (large return periods) required for the design of these facilities, the hazard is normally dominated by faults that are located within several kilometers of these sites. This places emphasis on the evaluation of the seismogenic potential of these nearby faults rather than on a regional evaluation of seismic hazards as is more common.

Several problems arise when evaluating seismic hazards from individual faults. The first is that the historical seismicity is seldom adequate to statistically predict the occurrence of earthquakes on an individual fault, especially for the long recurrence intervals of interest for critical facilities. The second problem concerns the prediction of strong ground motion within the near-source region of the fault where strong-motion data from major earthquakes have been extremely limited in the past. A third problem concerns the geometry of the fault plane which can have a significant effect on the computed level of hazard for sites very near the fault. The last problem concerns facilities located very near or within the fault zone where there exists the potential for surface rupture. A methodology for evaluating seismic hazards that accommodates each of these specific problems is discussed in the remainder of this paper. Based on the experience of the author, this methodology has evolved from direct application of its techniques to the probabilistic assessment of seismic hazards associated with critical facilities located in California and Nevada.

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ESTIMATE OF SEISMICITY

Where historical earthquakes are limited and there exists a clear relationship between geotectonics and earthquake occurrences, the inferred history of deformation is the best means of establishing the potential for future activity (Ref. 1). For faults, this deformation is usually given in terms of slip rate, defined as the mean relative displacement per year. Regional deformation is usually given in terms of strain rate. These rates of deformation may be established from geologic, geodetic, seismicity, and plate tectonic information (Ref. 2). This information is collectively referred to as seismotectonic data.

Using standard seismological relationships among seismic moment, slip rate, earthquake recurrence rate, and magnitude, several investigators (Refs. 2-9) have developed expressions relating seismicity to seismotectonic data. Each has assumed earthquake magnitudes to be exponentially distributed, thereby, generalizing the procedure proposed in Ref. 10.

The relationship developed in Ref. 9 has been used to estimate the mean rate of occurrence of earthquakes from slip rate because their use of a doubly truncated exponential distribution to model the relative frequency of earthquake magnitudes is consistent with that commonly used in the statistical analysis of earthquake occurrences. Their expression for the mean rate of occurrence of earthquakes having magnitudes greater than m_o is given by the relationship

$$\nu_o = \frac{\mu A_o S(c_2-b)}{K_o b} [M_o(m_u)10^{-b(m_u-m_o)} - M_o(m_o)]^{-1} \tag{1}$$

where μ is shear modulus, A_o is the total area of the fault plane, S is slip rate (tectonic rate minus creep rate), b is Richter b-value, $M_o(m_u)$ is the seismic moment of the upper bound magnitude for the fault, and $M_o(m_o)$ is the seismic moment of m_o. The magnitude m_o represents a physical lower limit below which earthquakes either are not expected to occur or do not contribute to the observed slip on the fault, and is not to be confused with m_1, the arbitrary lower threshold of magnitude used to quantify seismicity (note that $m_o \leq m_1$). The truncation factor K_o is given by the equation

$$K_o = \{1 - \exp[-\beta(m_u-m_1)]\}^{-1} \tag{2}$$

where $\beta = b \log_e 10$. Seismic moment and the parameter c_2 are defined from the expression

$$\log_{10} M_o(m) = c_1 + c_2 m. \tag{3}$$

In order to estimate ν, the mean rate of occurrence of earthquakes greater than some arbitrary magnitude m_1, we must evaluate the expression

$$\nu = \nu_o[1 - F(m)] \tag{4}$$

which, based on the doubly truncated distribution of magnitudes [F(m)] used to establish ν_o, becomes

$$\nu = \nu_o(1 - K_o\{1 - \exp[-\beta(m_1 - m_o)]\}). \tag{5}$$

If there exists no physical basis to support a lower bound for magnitude on a fault (i.e., $m_o << 0$) or if $m_u >> m_o$, then Eq. (5) can be simplified considerably, resulting in the relationship

$$\nu = \frac{\mu A_o S}{M_o(m_u)} \frac{c_2 - b}{b} 10^{b(m_u - m_l)}. \quad (6)$$

This expression for ν is equivalent to that originally developed by the author (Refs. 4 and 5) and consistent with the expressions for seismic moment release rate presented in Refs. 6 and 7.

The magnitude distribution parameter β (or b) is proportional to the inverse of the mean magnitude of a sequence of events. This makes its estimation from geological data alone very difficult. Microfracturing studies of rock in the laboratory and observations of earthquake sequences have led several investigators to suggest a possible relationship between b and seismotectonic data (e.g., Refs. 11 and 12). Until a more thorough understanding of the relationship between β and seismotectonic data becomes available it will be necessary to estimate this parameter from actual earthquake sequences. Microearthquakes, main shocks, aftershocks, and earthquake swarms occurring within the region of interest or within geotectonically similar regions may give statistically significant estimates of β.

If there are documented historical occurrences of earthquakes on the fault, then they may be used in conjunction with Bayesian probability theory to update seismotectonic estimates of the seismicity parameters ν and β (e.g., Ref. 2). The use of both types of data has the potential to produce an even more reliable estimate of seismicity than is possible from either type of data when used alone.

NEAR-SOURCE GROUND MOTION

The recent expansion of strong-motion networks throughout the world has been responsible for the recording of several signficant accelerograms in the near-source region of moderate-to-large earthquakes, an area where data have been severely lacking in the past. Three significant events which have occurred within the past 5 years are the 1976 Gazli, USSR (M_s 7.0), the 1978 Tabas, Iran (M_s 7.4), and the 1979 Imperial Valley (M_s 6.9) earthquakes, each producing accelerograms within 10 km of the fault.

These and other recent near-source recordings together with selected near-source data recorded as early as 1933 were used to analyze the behavior of peak horizontal acceleration (PGA) near the causative fault (Ref. 13). The goal was to make PGA predictions at these distances as generally reliable as far-field estimates. The study was restricted to the near-source region of earthquakes of magnitude 5.0 or greater to eliminate the small accelerations generally considered to be of little importance in earthquake engineering. This restriction substantially reduced the uncertainty in the analyses and enhanced the statistical significance of the results.

Due to the paucity of near-source data for large earthquakes, the study was not restricted to accelerations recorded in western North America. We acknowledge that the tectonics and recording practices of other countries may be substantially different from those in the Western United States, but these possible differences are far outweighed by the important contribution these foreign data make to understanding the behavior of near-source gound motion.

Several factors have minimized the potential bias of the foreign data used in the analyses. First, the restriction to the near-source region has made differences in anelastic attenuation negligible compared to the inherent scatter from other factors. In addition, the foreign data used in this investigation come from events occurring along tectonic plate boundaries which are generally similar to the interplate earthquakes of western North America. Deep subduction events were excluded because of the substantial difference in travel paths and stress conditions compared to the shallow events used in this study. All the foreign data were recorded on instruments having dynamic characteristics similar to those commonly used in the United States to avoid a possible instrument bias for these recordings. Such a bias has been systematically observed for the SMAC strong-motion accelerograph generally used in Japan.

The data base used in the analyses was assembled using criteria designed to select only consistent and quality data in the range of magnitudes and distances of interest for most design applications. The data base consisted of 27 earthquakes representing 229 horizontal components (116 records) of peak ground acceleration recorded at distances from the rupture zone of less than 30 or 50 km, dependent on magnitude. These data were weighted, by earthquake, within several distance intervals to control the effects of well-recorded events such as the 1979 Imperial Valley and the 1971 San Fernando earthquakes. A description of the selection criteria as well as definitions of important parameters of this selected data base are given in Refs. 13 and 14.

The mathematical relationship used for modeling the attenuation of near-source peak acceleration is expressed by the equation

$$PGA = 0.0159 \exp(0.868M)[R + 0.0606 \exp(0.700M)]^{-1.09}. \qquad (7)$$

where PGA is peak horizontal ground acceleration, R is closest distance to the fault rupture plane, and M is M_L for $M < 6.0$ or M_s for $M \geq 6.0$. This expression was determined from a nonlinear weighted regression analysis on the natural logarithm of PGA using the method of least squares. All the coefficients were found to be statistically significant at levels of confidence exceeding 99 percent based on empirical distributions of the coefficients developed using procedures set forth in Ref. 15. The 84th-percentile value of PGA is obtained by multiplying the median value by a factor of 1.45 representing a standard error of 0.372 on the natural logarithm of PGA. The goodness-of-fit is represented by an r^2 value of 0.81.

In a subsequent study, Campbell (Ref. 16) has identified several factors that significantly influence the near-source behavior of recorded ground motions. These factors include the topography of the site, the size and embedment of the structure housing the instrument, and the faulting mechanism of the earthquake. While not considered in the estimation of seismic hazards using the current methodology, relationships accommodating the latter two factors have been developed (Ref. 16) and represent an advancement of the current technology.

GROUND-MOTION HAZARD

The models for seismicity and peak acceleration presented in the preceding two sections were used in conjunction with the probabilistic hazard model developed in Ref. 17 to estimate the probability of exceedance (or return period) associated with various levels of PGA. This model includes a rigorous three-dimensional geometric model of the fault zone. Such a model is extremely important when assessing the hazard due to ground shaking for sites located near the fault. Experience has demonstrated that the computed hazard is very sensitive to both the length and width of the fault zone, the angle of dip of the fault plane, the size and location of fault rupture during individual events, and the position of the site with respect to the fault; features included in the model.

In the overall approach, each fault system is divided into a series of segments of equal seismicity. Within each segment, earthquakes are assumed to occur at random as a Poisson process. The distribution of these events, with respect to magntitude, is consistent with a doubly truncated exponential distribution. Fault rupture is taken into account through an empirical relationship between magnitude and fault length. The random occurrence of all events from all fault segments, when combined with a peak acceleration scaling relationship, is used to develop a probability distribution of peak acceleration at the site. A detailed description of the mathematics of this development may be found in Ref. 17.

FAULT-RUPTURE HAZARD

Fault rupture hazard is defined as the probability that the maximum surface displacement at a point on the fault exceeds some specified value over the time period of interest. The general approach is similar to that used in assessing ground-motion hazard. Each fault system is divided into a series of segments of equal seismicity. Earthquake occurrences within each segment are treated as Poisson processes with their magnitudes distributed exponentially. The random occurrence of all events from each fault is combined with a fault rupture model to develop a probability distribution of surface displacement for any point on the fault.

The three fault rupture parameters required in the development of the hazard model are fault rupture length (L), fault rupture displacement (D), and fault rupture radius (R). Models used to estimate these parameters from earthquake magnitude may be taken from the literature or developed independently from existing data. An application based on existing data may be found in Ref. 18.

For an earthquake of given magnitude and location, the probability of observing a displacement greater than a specified level at a point on the fault is comprised of a joint probability of three events. The first is the probability that surface rupture occurs, which we will designate as "event E_s." The second is the probability that surface rupture extends at least as far as the point of interest (designated as "event E_l"). The last is the probability that the displacement exceeds the specified value (designated as "event E_d").

Mathematically, this joint probability may be expressed as

$$P(D>d|M,x) = P(E_d \cap E_1 \cap E_s) \tag{8}$$

where M is the magnitude under consideration and x is the horizontal distance along the fault trace from the midpoint of fault rupture to the site. Simplifying Eq. (8) by means of conditional probability theory gives

$$\begin{aligned} P(D>d|M,x) &= P(E_d|E_1 \cap E_s) \cdot P(E_1 \cap E_s) \\ &= P(E_d|E_1 \cap E_s) \cdot P(E_1|E_s) \cdot P(E_s) \end{aligned} \tag{9}$$

with all events being contingent upon the occurrence of a given earthquake.

Surface rupture during a given earthquake is assumed to occur if the source radius (R) of the event is greater than the distance w measured along the width of the fault plane from the center of rupture to the ground surface. Since, for a given earthquake, the horizontal extent of faulting tends to be greater than the vertical extent, this definition of surface rupture is considered conservative for the purposes of estimating fault rupture hazard.

For a given magnitude M, we may compute source radius from an expression of the form

$$\ln R = A_R + B_R M. \tag{10}$$

Because of uncertainty in this expression, R may be considered a random variable. Let us assume R to be lognormally distributed with a median of ln R and a standard deviation σ_R (on ln R) equal to the standard error of estimate associated with Eq. (10). Then, the probability that R is greater than w (the event E_s) is given by

$$P(E_s) = P(R > w) = \Phi^* \left(\frac{\ln R - \ln w}{\sigma_R}\right) = \Phi^* (Z_R) \tag{11}$$

where $\Phi^*(Z_R)$ represents the complementary standard-normal cumulative distribution function $[1 - \Phi(Z_R)]$ of the standard variable Z_R.

Given that surface rupture occurs, let it be assumed that its length is equally distributed in both directions along the fault trace (i.e., bilateral rupture). The midpoint of this rupture is directly above the assumed point of initiation as measured along the fault width. For rupture to occur at the site of interest, it must be as long as twice the distance from the midpoint of the surface expression to the site, x. Therefore, rupture occurs at the site if $L > 2x$, where L is the surface rupture length as given by the expression

$$\ln L = A_L + B_L M. \tag{12}$$

To account for uncertainty in the regression, L may be considered lognormally distributed, with median ln L and standard deviation (on ln L) of σ_L. The probability of the event E_1 occurring (given event E_r), then becomes

$$P(E_1 \mid E_r) = P(L > 2x) = \Phi^* \left(\frac{\ln L - \ln 2x}{\sigma_L}\right) = \Phi^*(Z_L). \tag{13}$$

Given that surface rupture occurs and that it ruptures at least as far as the site, the surface displacement associated with the earthquake M may be estimated from the expression

$$\ln D = A_D + B_D M. \tag{14}$$

To account for uncertainty in this estimate, D is considered lognormally distributed with median ln D and standard deviation (on ln D) of σ_D. The probability that the displacement exceeds some specified value d then becomes

$$P(E_d \mid E_1 \cap E_s) = P(D>d) = \Phi^*\left(\frac{\ln D - \ln d}{\sigma_D}\right) = \Phi^*(Z_D). \tag{15}$$

The surface displacement hazard for a point on a fault trace associated with an earthquake of specified location and magnitude is obtained by substituting Eqs. (11), (13), and (15) into Eq. (9), thus obtaining the expression

$$P(D > d \mid M,x) = \Phi^*(Z_D) \cdot \Phi^*(Z_L) \cdot \Phi^*(Z_R) \tag{16}$$

The total hazard at the site of interest requires combining the hazards associated with all possible earthquakes hypothesized to occur on the fault. The development of this hazard is equivalent to the development of the ground motion hazard model described in Ref. 17 and will not be presented here. The reader is referred to this reference and Ref. 18 for this development.

CONCLUSIONS

The evaluation of seismic hazards for sites located near active faults has several important aspects not usually associated with seismic-hazard analyses. These aspects include (1) the domination of the hazard by a single fault, which requires an estimate of the seismicity independent of historical earthquake occurrences as well as consideration of the geometry of the fault plane, (2) the necessity of predicting strong motion within the near-source region of the fault, and (3) consideration of the potential for fault rupture beneath the facility.

A methodology for probabilistically estimating seismic hazards which incorporates these important aspects has been presented in this paper. It relies on the development of seismotectonic data on the fault zone under study and on hazard models that are capable of accommodating a three-dimensional description of the fault plane. This methodology has been successfully applied to the evaluation of seismic hazards at sites located in California and Nevada and has proved to be an effective means of assessing the seismic hazards associated with critical facilities.

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