Consideration of Source Parameter Uncertainties in the Geophysical Ground Motion Model

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INTRODUCTION

In recent years considerable research has been performed on seismic risk assessment of nuclear power plants. These studies show that estimation of seismic hazard should be consistent with earthquake recurrence patterns, the rupture mechanisms, the wave propagation path, and the local soil condition. Therefore a stochastic ground motion forecast model is proposed based on a geophysical ground motion model and a stochastic earthquake occurrences model. For an earthquake occurrence model, the random slip model is employed. For a ground motion model, the normal mode method is used. In particular uncertainties on stress accumulation rate due to inhomogeneous fault properties are considered to estimate the probabilities of earthquake occurrences in this study.

TIME-DEPENDENT EARTHQUAKE OCCURRENCE MODEL

In the area of earthquake prediction, Shimazaki and Nakata(1980) showed a positive relationship between the size of earthquakes and the time between events. They proposed two earthquake prediction models to represent the time-dependent characteristics of earthquake occurrences.

Using the basic concept of time-dependent behavior of Shimazaki and Nakata(1980), Kiremidjian and Anagnos(1984) developed the stochastic slip-predictable model. In the stochastic model, the temporal dependence of events is presented through semi-Markovian modeling, which considers that the joint probability of the next state and the time of the state change depends only on the present state of the process, and is independent of past earthquake history. However, direct application of the stochastic slip-predictable model tends to overestimate the earthquake recurrence times because of the assumption of a constant slip accumulation rate in time and space. Thatcher(1984) found a strong non-linearity of strain buildup based on geodetic observation. A study of large earthquakes in the Alaska peninsula (Li and Kisslinger,1985) also found that stress on a plate boundary accumulates non-linearly with time. Since the variation of a slip accumulation rate significantly influences the estimation of earthquake recurrence times, it is necessary to develop a more realistic earthquake prediction model. Therefore, a stochastic slip-predictable model with a random slip rate, which includes effects of non-uniform slip accumulation rate and its uncertainties is developed in this paper.

STOCHASTIC SLIP-PREDICTABLE MODEL WITH A RANDOM SLIP RATE

In the slip-predictable model of Kiremidjian and Anagnos(1984) it is assumed that stress accumulates at a constant rate starting from some initial stress level. When an earthquake occurs, all stress release during an earthquake. Then stress accumulates again from an initial stress level. Figure 1a shows the stress accumulation and its release on a segment of a fault in their model. The main characteristics of the model is that future earthquakes depend on the time of occurrence of the last event and do not depend on the size of the last event. Thus the longer the elapsed time since the last earthquake, the larger is the magnitude of the next earthquake.

Although the stress accumulation rate is relatively constant in terms of the long time prediction, the actual stress accumulation and its release process do not strictly follow the slip predictable model with a constant slip rate. The slip rate for each earthquake may change significantly due to the presence of strength and stiffness heterogeneities of a fault plane as shown in Figure 1c. Therefore, a random slip rate is employed to estimate probabilities of earthquake occurrences

The concept of the random slip rate includes the effects of heterogeneous material strength, nonlinear stress or strain accumulation rates, and unknown initial stress levels. Figure 1b shows the stress accumulation and release on a segment of the fault in the slip-predictable model with a random stress accumulation rate. The process starts from an initial stress level i at a random stress accumulation rate until an earthquake occurs. The size of the earthquake event is governed by the stress release level, but is not directly proportional to the elapsed time since the last event. The size of the earthquake is dependent not only on the elapsed time since the last event but also on the stress accumulation rate.

The model is not restricted to the stress level as the earthquake measuring parameter. Other parameters, such as coseismic slip, seismic moment, or magnitude could be used. Since the size of the earthquake is not well correlated by the stress drop, the state of the process is defined by magnitude ranges associated with the amount of coseismic slip.

FORMULATION OF THE RANDOM SLIP RATE MODEL

In the slip-predictable model, earthquake occurrences are considered to be a time-dependent sequence of events. A Markov renewal model (Kiremidjian and Anagnos, 1984) is used to represent the time-dependent behavior of earthquake sequences. This model is extended to a more general time-dependent model which includes non- uniform stress accumulation on a fault plane. The formulation of the slip-predictable model with a random slip rate is briefly summarized in this section

It is assumed that there are N discrete magnitude levels which form the state space of the model E={ 1,2,....,N }. Let

Y_n=a random variable describing the magnitude of the nth event

and

T_n=the time of the nth event

Thus the set $\{Y_n : n \geqq 0\}$ are random variables assuming values in E, and the set $\{T_n : n \geqq 0\}$ are such that $0 < T_0 < T_1 < \dots$ The stochastic process $\{(Y_n, T_n : n \geqq 0)\}$ is a Markov renewal process provided that

$$P[\,Y_{n+1} = j\,, T_{n+1} - Tn \;\leqq t \mid Y_0, \dots, Y_n\,; T_0, \dots T_n]$$

$$= P[\,Y_{n+1} = j\;, T_{n+1} - T_n \;\leqq t \mid Yn = i\,] = Q\,(i,j,t) \qquad (1)$$

$$\text{for all } i, j, \text{ and } t \geqq 0$$

With the assumption of the slip-predictable model, the joint probability of Y_{n+1} and $T_{n+1}-T_n$ does not depend on the present state. The probabilities are also independent of past history.

The time-transition probabilities Q(i,j,t) of the Markov process $\{(Y_n, T_n) : n > 0\}$ are obtained by the cumulative interarrival time distribution, $F_{T_{ij}}(t)$, as follows:

$$Q\;(i,j,t) = F_{T_{ij}}(t) \qquad\qquad t \geqq 0 \qquad\qquad (2)$$

The one step transition probabilities for the process are given by

$$p_{ij} = \lim_{t \to \infty} Q(i,j,t) \tag{3}$$

The complementary cumulative holding time distribution are given by

$$H_{ij}(t) = 1 - Q(i,j,t)/p_{ij} \qquad for\ i,j=1,2,.....N\ \ and\ \ t \geqq 0 \tag{4}$$

The holding time distributions are obtained by differentiating equation (4).

$$h_{ij}(t) = -\frac{d}{dt}[H_{ij}(t)] = \frac{d}{dt}\left[\frac{Q(i,j,t)}{p_{ij}}\right] = \frac{1}{p_{ij}} f_{T_{ij}}(t) \tag{5}$$

Then the probability of at least one event of size $Y \geqq j$ in time $(t_1,t]$, denoted by $G_i(Y \geqq j, k \geqq 1, t_1|t)$ is given by

$$G_i(Y \geqq j, k \geqq 1,\ t_1|t) = 1 - G_i(Y \geqq j, k=0, t_1|t)/H(t_1) \tag{6}$$

where

$$G_i(Y \geqq j, k=0, t_1|t) = \sum_{r=1}^{j-1} \int_{t_1}^{t} p_{ir} h_{ir}(\tau) G_r(Y \geqq j, k=0|t-\tau)\, d\tau + H(t) \tag{7}$$

and

$$H(t) = \sum_{j=1}^{N} H_{ij}(t)\, p_{ir} \tag{8}$$

Bayesian Approach of Slip-predictable Model

For the application of the model, it is necessary to obtain estimates on the interarrival time distribution, $F_{T_{ij}}(t)$ conditional on the size of next event. However estimation of the cumulative interarrival time distribution is often difficult because of the lack of the data. Therefore, the Bayesian technique is used to determine the distribution parameters. The geophysical information on coseismic slip rates is used to estimate the prior distribution parameters. Then historical data are combined to determined the posterior distribution of the interarrival time.

Following the development of Kiremidjian and Anagnos(1984), the interarrival times of a process are assumed to be Weibull distributed. For the Weibull distribution, the closed form of Bayesian posterior distribution is not available. A numerical integration approach is used to determine distribution parameters. Since we do not have enough data to determine the prior distribution of the Weibull parameters, it is assumed that these parameters are uniformly distributed. Then the posterior distribution of the cumulative function is computed by a numerical integration method. (Sinha,1986; Suzuki 1988). The prior and posterior distributions of cumulative interarrival times in the Middle America Trench are shown in Figure 2.

THEORETICAL GROUND MOTION MODEL

A large number of empirical ground motion attenuation relationships have been proposed. However, none of them fully and satisfactorily describe the ground motions at a site. Characteristics of ground motion of importance in earthquake-registant design, such as predominant periods, number of peaks above a certain level of ground motion, or effects of directivity are most often omitted.

In this study the normal mode method is used to simulate a site ground motion. This approach is selected primarily because characteristics of ground motion at a site can be obtained based on the source mechanisms, the wave propagation path, and the local soil conditions in a region.

The method is composed of the two steps: (a) computation of the normal modes representing the free oscillations of the earth and (b) site response analysis by the weighted superposition of these modes. In order to simulate ground motions at a site, a series of filters related to the finite dislocation rise time, the finite rupture length, and attenuation are applied. The high frequency waves which are of primary interest for the seismic design are generated by the asperity model (Kanamori and Stewart,1978) and the stochastic fault model (Koyama,1985).

The site ground motions are computed by superposition of ground motion responses from individual patches along the rupture area of the fault. A large number of ground motions at a site are simulated considering uncertainties in source parameters such as fault geometries, rupture velocity, rise time, fault dimensions, patch length and seismic moment. These ground motions are used to understand the characteristics of ground motions at a site. A more detailed discussion of the geophysical ground motion model is given by Schoof (1984) and Suzuki (1988). Then the ground motion model is combined with the stochastic slip-predictable model with a random slip rate to estimate the probabilities of exceedence of ground motion levels.

Application of The Model

The slip-predictable model with a random slip rate is applied to the Guerrero region along the Middle America Trench, since the next large earthquake is expected to occur in this region. The location of the Guerrero gap and the aftershock area along the Middle America Trench are shown in Figure 3. Assessment of the probabilities of earthquake occurrences in the gap has been difficult because of the lack of data. For this reason, the proposed model with Bayesian parameter estimates is particularly useful for this region. The probabilities of earthquake occurrences for the Guerrero gap are first computed by the random slip model. Figure 4 shows the probabilities of at least one event greater than or equal to magnitude Ms=7.5 and 8.0 in the next 50 yr, as function of seismic gaps.

In the next application, the geophysical ground motion model is combined with the random slip rate model. Risk-consistent response spectra, which correspond to a given probability of exceedence of response values are obtained using random source parameters. Figure 5 shows such risk-consistent response spectra for the probabilities of exceedence of 0.1 and 0.5 on a firm and soft soil site in Mexico City in 50 yr due to earthquakes in the Guerrero region. 75 yr seismic gap is considered. The solid lines correspond to forecasts using a random slip rate model and the dashed lines correspond to forecasts using a constant slip rate model. The results show that the ground motion forecast model with a constant stress accumulation rate tends to overestimate site ground motion levels.

Since risk-consistent response spectra include much information on characteristics of ground motions at a site, use of these spectra is proposed for seismic design of nuclear power plants.

CONCLUSION

The results of this study indicate that consideration of uncertainties on earthquake source parameters is important to estimate seismic risk of a nuclear power plant. Uncertainties on stress accumulation rate in the stochastic slip-predictable model is particularly important to estimate the probabilities of earthquake occurrences. The proposed model represents considerable improvement over existing empirical ground motion models with constant source parameters.

REFERENCES

Kanamori, H. and G. S. Stewart, Seismological aspects of the Guatemala Earthquake of February 4, J. Geophys. Res., 83, 3427-3434, 1978

Kiremidjian, A and T. Anagnos, Stochastic Slip-predictable Model for Earthquake Occurrences, Bull. Seism. Soc. Am. 74(2), 739-755, 1984

Kiremidjian, A. and S. Suzuki, A Stochastic Model for Site Ground Motions from Temporally Dependent Earthquakes, Bull. Seism. Soc. Am., 77(4), 1110-1126, 1987

Koyama, J .Earthquake Source Time Function from Coherent and Incoherent Rupture, Tectonophysics, 118, 227-242, 1985

Li, C. , and C. Kisslinger, Stress Transfer and Nonlinear Stress Accumulation at Subduction-type Plate Boundaries, In Earthquake Prediction, K. Shimazaki and W. Stuart (Eds.), Birkhauser, Basel, pp. 812-892,1985

Schoof, C., Geophysical Input for Seismic Hazard Analysis, Ph.D. Diss., Dept. Civil Engrg., Stanford Univ., CA 1984

Shimazaki, K. and T. Nakata, Time Predictable Recurrence for Large Earthquakes, Geophys. Res. Lett., 7, 279-282, 1980

Sinha, K. S. Bayesian Approximation and Reliability Estimation , In Reliability and Life Testing, John Wiley & Sons, New York, 1986

Suzuki, S., A Stochastic Ground Motion Forecast Model with Geophysical Considerations, Ph.D. Diss., Dept. Civil Engrg., Stanford Univ., CA, 1988

Suzuki, S., and A. Kiremidjian, Site Hazard Analysis Methods with Empirical and Geophysical Ground Motion models. Report No. 80, The John A. Blume Earthquake Engineering Center, Dept. of Civil Engineering, Stanford Univ., CA 1986

Thatcher, W. The Earthquake Deformation Cycle at the Nankai Trough, Southwest Japan, J. Geophys. Res., 89, 3087-3104, 1984

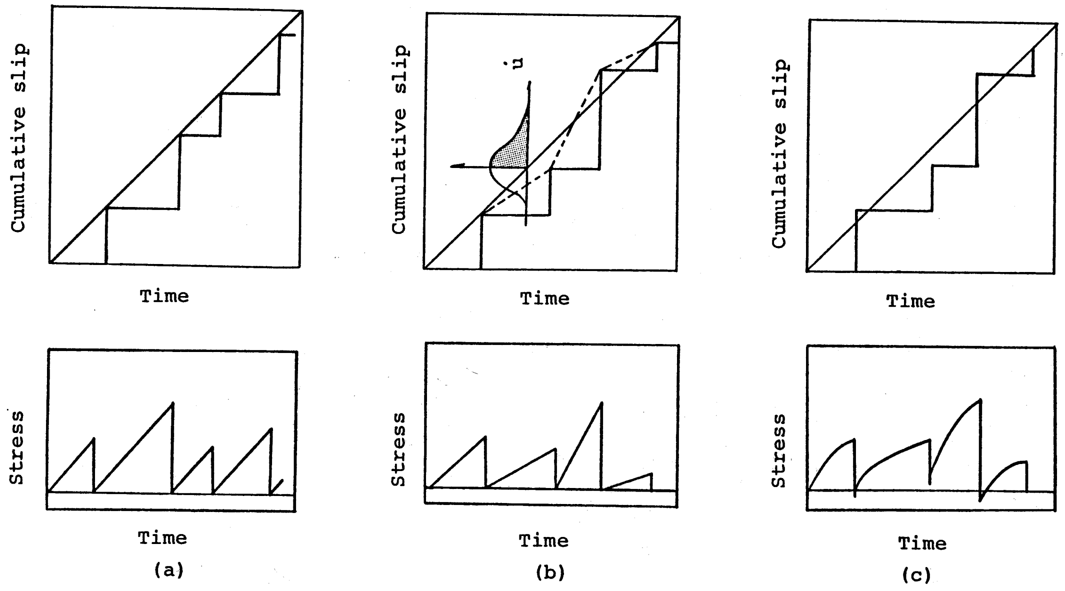
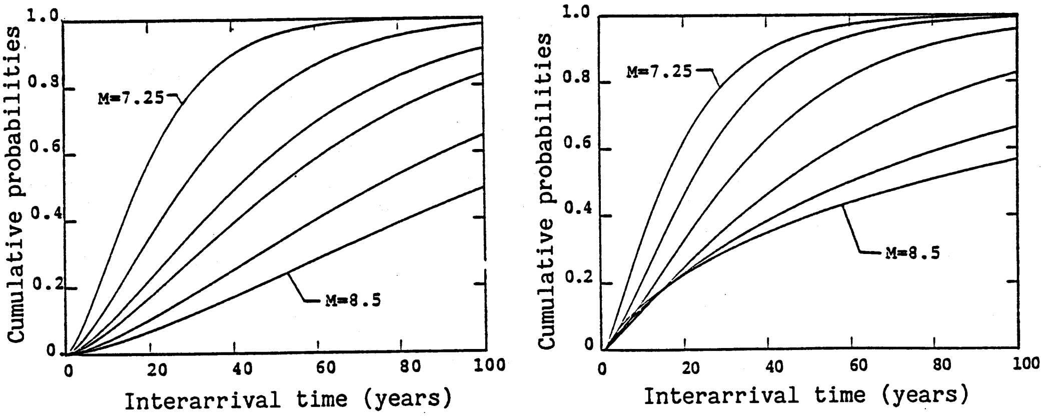
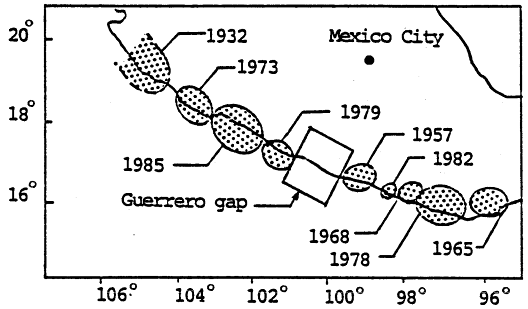


Figure 1. Schematic representation of time-dependent behavior: (a) a constant slip rate model ; (b) a random slip rate model ; (c) actual stress accumulation and its release.



(a) (b)

Figure 2. Cumulative holding time distribution along the Middle America Trench between 96°W and 104°W : (a) prior ;(b) posterior distribution.



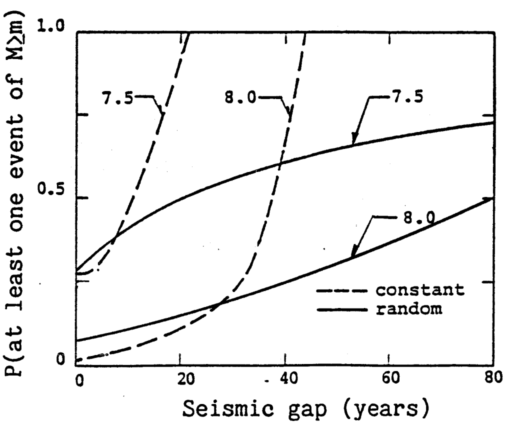
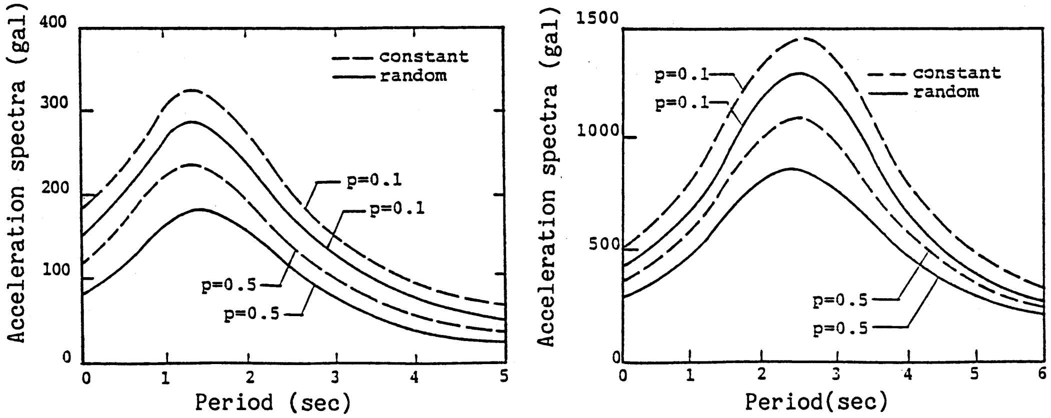


Figure 3 Location of the Guerrero gap.

Figure 4. Probabilities of at least one event in the next 50 yr for Guerrero earthquakes.



(a) (b)

Figure 5. Risk-consistent response spectra in Mexico City due to earthquakes in the Guerrero region: (a) on a firm soil; (b) on a soft soil site.