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A stochastic ground motion model with geophysical consideration

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ABSTRACT: The normal mode method is used to develop the theoretical attenuation relationships based on the regional geophysical information. The stochastic model which considers random dislocation process in time and space is used for simulating ground motions in the higher frequency range. The model is used to simulate ground motions in the San Francisco Bay region using the fault mechanisms of the Loma Prieta earthquake of October 17,1989.

1 INTRODUCTION

In seismic site hazard estimation, ground motions are traditionally estimated using attenuation relationships developed from empirical data. Such data are limited resulting in large variability in predicted ground motions. Frequently, the error margin is a factor of two or greater causing greater difficulties in design decisions. Furthermore, the geophysical characteristics of the earthquake source and wave propagation are usually ignored in the simple attenuation functions.

With the increased computational capabilities, there has been an increased need for forecasting time histories as well as response spectra from future earthquake events rather than forecasting simple peak acceleration values. In order to fulfill this need, more complete information on future ground motions is required.

In an area of predicting earthquake ground motions, several techniques have been used to simulate ground motions which consider the fault rupture mechanisms and the propagation of various seismic waves from the source to the site. These include the ray tracing methods (Chapman, 1985) , elasto-dynamic Green's functions (Apsel and Luco, 1983), empirical Green's functions (Tanaka et al., 1982) and the normal mode method (Schoof, 1984). However, few of these methods have been utilized in engineering practice. It is recognized that no one method fits all geologic or tectonic regimes, and each method has advantages in some particular situations. Some of advantages and disadvantages of these methods were discussed in the paper of Suzuki and Kiremidjian (1988).

In this paper we adopt the normal mode method to simulate the site specific ground motion and to obtain the spectral attenuation relationships based on the simulated ground motions. An important advantage with the normal node method is that the fault rupture process and the computation of the normal modes can be treated separately. Once the eigenvalues and eigenfunctions for the earth are evaluated, a large number of ground motion can be generated for different source-to-site distances and source parameters enabling the computation of theoretical attenuation relationships.

2 Ground motion simulation Model

2.1 The Normal Mode Analysis Method

The normal mode method is composed of two steps:(a) computation of the normal modes representing the free oscillations of the earth and (b) site response analysis by weighted superposition of these modes. In order to compute the normal modes, the earth is assumed to be an elastic spherical body whose free oscillations are described by the elementary equation of free vibrations given by

$$|K - \omega^2 M| = 0 \tag{1}$$

where K is the stiffness matrix, M is the consistent mass matrix and ω is the circular frequency of the earth. The eigenvalues and eigenfunctions that describe the normal modes of vibration of the earth are solution of the homogeneous differential equation of a motion. Two independent modes are identified: the toroidal modes corresponding to a twisting motion of the earth(SH waves) and spheroidal modes corresponding to distorting motions of the earth(P,SV waves). In computing the eigenvalues and eigenfunctions, the sphere is considered to be radially heterogeneous and laterally homogeneous. The excitation function for computing the response motion at a site is models as a double couple force. The equations for the toroidal and spheroidal modeled excited by a point source double couple are given in Suzuki and Kiremidjian(1988).

The rupture at a finite fault is modeled as a moving source. The response of the ground motion at a site $u(\omega)$ is expressed by a series of filters

$$u(\omega) = S(\omega) \cdot F(\omega) \cdot X(\omega) \cdot Q(\omega) \cdot L(\omega) \quad (2)$$

where $S(\omega)$ is the Fourier transform of the source time function.$F(\omega)$ represents the disloation prosess along the source. $X(\omega)$ represents the wave propagation effect. $Q(\omega)$ is the attenuation effect from the source to the site and $L(\omega)$ is the local soil filter.

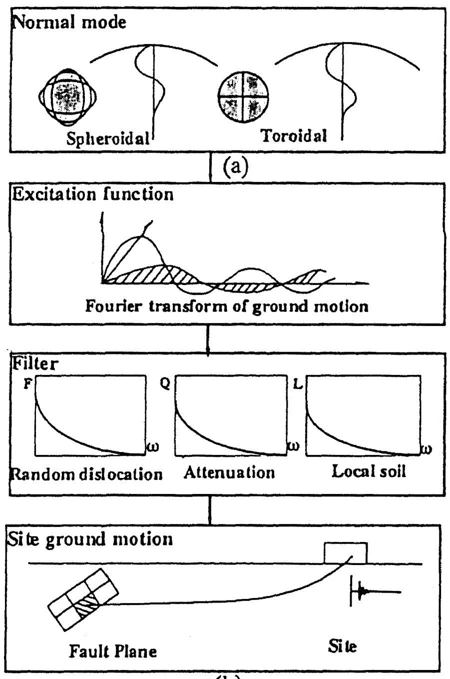

Figure 1 Schematic representation of (a) normal mode method and (b) site response analysis

2.2 Random Dislocation Process

2.2.1 Introduction

We next consider the dislocation spectra $F(\omega)$. The long period seismic motions from large earthquakes are well represented when the rupture along the source is assumed to be smooth and is represented by a deterministic function. Heterogeneities along the fault plane, however, are believed to cause complex rupture process resulting in higher frequency ground motions (Boore and Joyner 1978). For engineering purposes it is important to represent these higher frequency components of the ground motion. Thus a random fault process in time and space is adopted for simulating higher frequency waves.

2.2.2 Random Dislocation Process in Time

Following Koyama (1985) the dislocation velocity at the source is defined as $\dot{D}(t)$. For a coherent rupture process, the dislocation velocity is taken to be constant over the duration of rupture. When considering inhomogeneous rupture, the dislocation velocity is assumed to be a random pulse process. The height of the pulses is random and the duration of each pulse τ is exponentially distributed according to $\exp(-\lambda\tau)$ where λ is the rate of pulse occurrences.

Following Boore and Joyner (1978)integration, the finite dislocation rise time filter for the random dislocation in time $F_t(\omega)$ is found to be

$$F_t(\omega) = \left[\left(\sin\frac{(\omega T_0/2)}{(\omega T_0/2)}\right)^2 + \frac{2\sigma^2}{T_0^2\;2}\left\{\frac{\omega^2-\lambda^2}{(\omega^2+\lambda^2)^2} + \frac{\lambda T_0}{\omega^2+\lambda^2}\right\}\right]^{\frac{1}{2}} \quad (3)$$

The first term in equation 3 corresponds to the smooth rupture process with a smooth dislocation velocity in time. The second term describes the ramdom rupture process with random dislocation velocity in time due to fault patches The patch density λT_0 (i.e.; the number of patches along the fault plane) and σ (i.e.; the fluctuation in the velocity) are govern the high frequency.

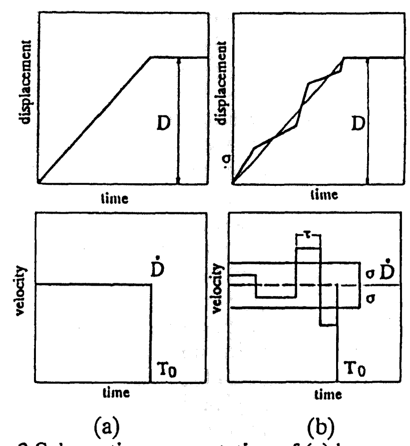

Figure 2 Schematic representation of (a) homogeneous (b) random dislocation process

2.2.3 Random Dislocation Process in Space

The source spectrum for the random dislocation process in space is employed. In order to include the effect of the random dislocation process in space a fault randomly distored in space is considered. The source spectrum for the randomly distorted fault plane is obtained by a weighted sum of the source spectrum for the trigonometrically distorted fault plane as follows

$$F_L(\omega) = \sum \alpha_i F_{iL}(\omega) \quad (4)$$

where α_i is the random weighting factor with $\sum\alpha_i = .1$. $F_{iL}(\omega)$ is the source spectrum of the trigonometrically distorted fault plane whose wave length and amplitude are λ_i and Δh_i as shown in Figure 3. The schematic representation of the randomly distorted fault is shown in Figure 3.

For the trigonometrically distorted fault the amplitude $h_i(\xi)$ in distortion of a fault plane is given by

$$h_i(\xi) = \Delta h_i \sin(2\pi\xi/\lambda_i) \qquad (5)$$

The source spectrum for the trigonometrically distorted fault plane is given by Miyatake(1985)

$$F_{iL}(\omega) = a_{i0}\frac{\sin\frac{\omega\Phi_0}{2}L}{\frac{\omega\Phi_0}{2}L} + \frac{a_{i1}}{2}\left\{\frac{\sin\frac{k_i+\omega\Phi}{2}L}{\frac{k_i+\omega\Phi}{2}L} + \frac{\sin\frac{k_i-\omega\Phi}{2}L}{\frac{k_i-\omega\Phi}{2}L}\right\} \qquad (6)$$

$$+ \frac{a_{i2}}{4}\left\{\frac{\sin\frac{2k_i+\omega\Phi}{2}L}{\frac{2k_i+\omega\Phi}{2}L} + \frac{\sin\frac{2k_i-\omega\Phi}{2}L}{\frac{2k_i-\omega\Phi}{2}L} + \frac{\sin\frac{\omega\Phi}{2}L}{\frac{\omega\Phi}{2}L}\right\}$$

and

$$\Phi = \frac{1}{V_r} - \frac{\cos\theta_0}{\beta} \qquad k_i = 2\pi/\lambda_i \qquad (7)$$

where a_{ik} is the constant of Taylor expansion of cos 2θ and L is the rupure length. V_r and β are the rupture and wave velocity respectively.

The complete form of the random dislocation process in time and space is obtained by combining equation 3 and 6 .

$$F(\omega) = F_t(\omega)\, F_L(\omega) \qquad (8)$$

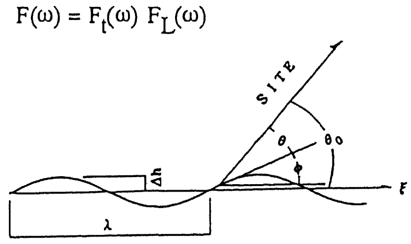

Figure 3 Trigonometrically distorted fault plane

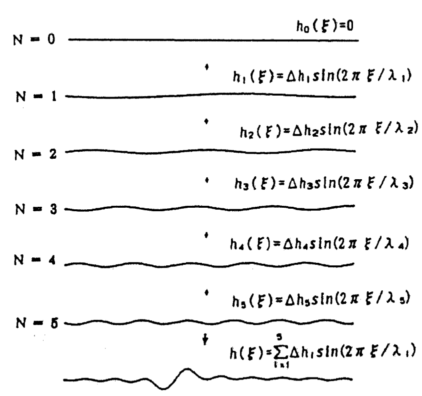

Figure 4 Schematic representation of the randomly distorted fault plane

3 APPLICATION OF THE MODEL

3.1 Introduction

In order to investigate the applicability of the model, the ground motions from the Loma Prieta earthquake are simulated. The same source mechanisms as the events are used to simulate the motions. The results are compared with the observed records to demonstrate the effectiveness of the model. The ground motions from San Andreas fault are simulated using the random dislocation process in time and space.

3.2 Simulation of Loma Prieta Earthquake

The Loma Prieta Earthquake of October 17, 1989 (M_S = 7.1) occurred in a segment of the San Andreas fault northeast of Santa Cruz, California. The epicenter was located 16 km northeast of Santa Cruz and 30km south of San Jose. The main rupture started at a depth of 15km and the total rupture length is 40km.

In order to examine the applicability of the geophysical ground motion model to this region, the strong ground motions of the Loma Prieta earthquake are simulated. The rupture is assumed to start at the center of the fault plane and is propagated in both directions at a speed of 2.5km/sec . The fault plane is divided into 8 asperities. The asperity length and the rise time are assumed to be 5km and 2.5sec respectively, following the study by Choy and Boartwright (1990). The source parameters used for the simulation are shown in Table 1.

Table 1 Source parameters used for the simulation

Seismic moment	M = 3.0 x 10^{26} dyne-cm
Rupture length	L = 40 km
Rupture width	W = 15 km
Source geometry	φ =128°
	δ = 70°
	λ =138°
Rise time	τ = 2.5 sec
Rupture velocity	v = 2.5 km/sec
Patch length	l = 5 km
Quality factor	Q = 200

Figure 5a shows the simulated time histories of the strong motion acceleration at rock site from 20 km of the source as obtained by the model together with the observed records (Shakal et al., 1989) at Corralitos-Eureca Canyon Rd. The simulated time histories at rock sites in San Francisco are shown in Figure 5b together with observed records at Rincon Hill. Although the local geology and site condition are not included in the simulated ground motions, the shape of the time histories from the model are close to those of the observed records for the engineering purposes.

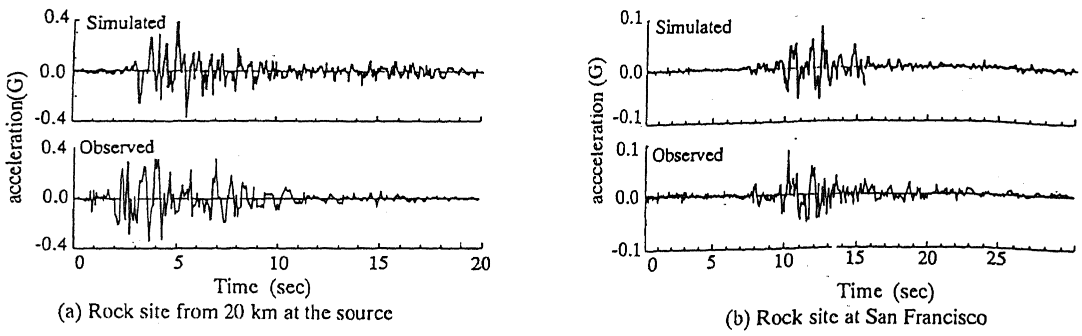

Figure 5 Simulated and observed ground acceleration of 1988 Loma Prieta earthquake

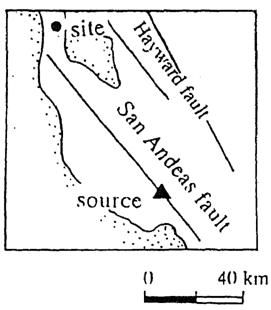

Figure 6 Source to site geometry for the simulation

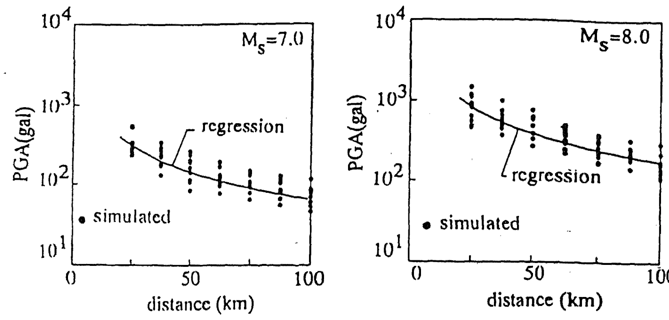

Figure 7 Theoretical attenuation relationships base on the theoretical ground motion model

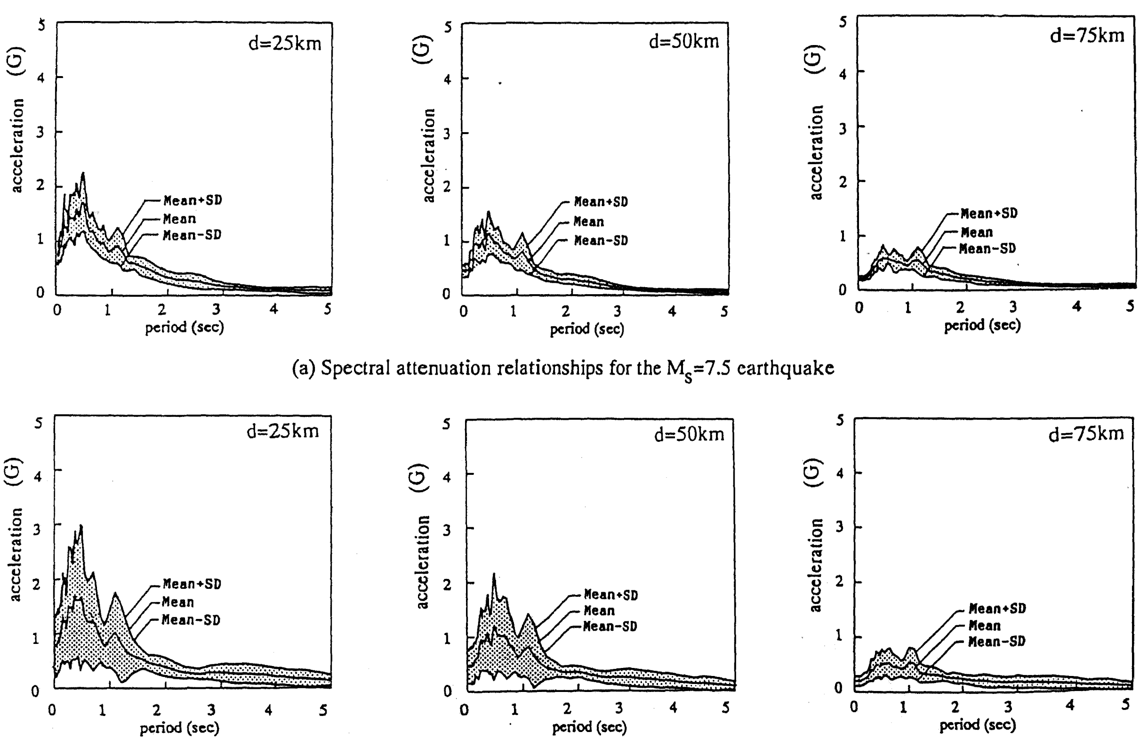

Figure 8 Spectral attenuation relationships by the geophysical ground motion model along the San Andreas fault

4 DEVELOPMENT OF SPECTRAL ATTENUATION

4.1 Introduction

The National Earthquake Prediction Council has been estimating the probabilities of earthquake occurrences along the San Andreas fault after the Loma Prieta earthquake. There is a high probability of a large earthquake occurrence along a segment of the San Andreas fault north of the Loma Prieta rupture zone and a segment of the Hayward fault. Therefore, it is very important to understand the characteristics of ground motions from the expected earthquake in order to reduce the damage. For that purpose, a large number of ground motions from the next earthquake along the San Andreas fault are simulated to understand the characteristics of ground motions. Since the source parameters are not deterministic but random for each event, the Monte Carlo simulation method is employed to estimate ground motions using random source parameters.

In this study the source parameters used for simulating ground motions are investigated first. Sensitivity studies on the mode number are also performed to determine the number of modes needed for the simulation. Then the attenuation relationships in terms of the peak ground acceleration and response spectra are developed.

4.2 Simulation of ground motions

4.2.1 Source parameters

Earthquake activity along the San Andreas fault system reflects brittle accomodation of the crust to the relative motion along the dextral transform boundary between the Pacific and North American plates. A large number of earthquakes along the San Andreas fault accommodate most of this relative earth motion.

In order to estimate the expected site ground motion from an earthquake along the San Andreas fault system, the regional characteristics of earthquake source mechanisms must be employed. In the geophysical ground motion model, eight parameters have to be determined: seismic moment, rupture dimension, rise time, rupture velocity, patch length, earth structure, and quality factor. The scaling laws for the above parameters are also necessary to estimate ground motions from different sizes of earthquakes. However, it is very difficult to determine some of these parameters, partly because of insufficient data and partly because of the complex earthquake mechanisms. Therefore, in this study, such parameters are considered as random variables.

4.2.2 Sensitivity studies on the mode number

In the normal mode method the computation of higher modes is necessary to simulate ground motions at the high frequency range. However the amplitude of a ground motion associated with higher modes is smaller than that with lower modes. Therefore, it is not necessary to include the higher modes which have little effect on the amplitude of ground motions. The determination of the minimum number of modes helps to decrease the computation time significantly. In order to determined the minimum number of modes, the contribution of each mode to the accelerelation level is investigated. Based on the sensitivity studies on the mode contribution, it is found that the amplitude of the ground motion acceleration associated with 50th modes is less than 1% of the sum of the amplitude of the 1st to 50th mode. Therefore, in this study the fundamental to the 50th modes are used for simulating the ground motions from the San Andreas fault.

4.2.3 Spectral Attenuation Relationships

Ground motions from the San Andreas fault are simulated by the model based on the regional geophysical parameters. These parameters are considered to be random and their distributions are summarized in Table 2. Several types of results are obtained in this study. First, the peak ground attenuation relationships are developed by simulating a series of ground motions by the model. Then the spectral attenuation relationships are computed for the different magnitude levels. Since most of the source parameters are randomly distributed, the Monte Carlo simulation method is used to estimated ground motions assuming different source parameters for each ground motion.

The fifty ground motions are generated for each magnitude level in order to obtain the mean and the standard deviation of the peak ground acceleration attenuation relationships. The peak ground acceleration attenuation laws for two magnitude levels (M_s = 7.0 and 8.0) in San Francisco are shown in Figure 4.6. The following relationships between the peak ground acceleration and the surface magnitude M_s is obtained by the regression analyses.

$$a_{max} = 0.0125\, e^{0.98Ms} R^{-1.13} \qquad (9)$$

where a_{max} is the peak ground acceleration in g. M_s is the surface magnitude and R is source to site distance in km.

Another interesting groui ı motion parameter for estimating the seismic hazard is the response spectrum. Fifty ground motion time histories obtained by the simulation are used to develop the spectral attenuation relationships along the San Ardreas fault. The relationships for two magnitud levels (M_s=7.5 and 8.0) are shown in Figure 8. The figure also shows the mean and the standard deviation of the response spectra for these magnitude levels.

From Figure 8, it is found that the shape of theresponse spectra changes significantly depending on magnitude and source-to-site distance. The amplitude in the long-period range tends to increase as the size of the

Table 2 List of source parameters and their distributions along the San Andreas fault

Parameters	Type of distribution	Mean value (Scaling law)	Ramarks
Seismic moment	Log normal distribution	$\log M_0=1.25M_S + 17.64$	San Andreas fault data
Fault length	Log normal distribution	$\log L=0.68M_S - 3.18$	San Andreas fault data
Fault width	Deterministic	$W=15$	San Andreas fault data
Fault geometry	Deterministic	Strike slip fault	San Andreas fault data
Rupture velocity	Log normal distribution	$V_r=0.72\beta$	world wide data
Rise time	Log normal distribution	$\tau=16\ (LW)^{1/2} / (7\pi^{3/2}\beta)$	world wide data
Patch length	Log normal distribution	$\log \rho=0.548M_S - 3.27$	world wide data

earthquake increases. It is also found that the amplitude in long-period range does not decay fast as the distance from the source increases.

These characteristics are consistent with those of observed ground motions along the San Andreas fault. Since the spectra obtained by the simulation method include regional earthquake source mechanisms and path effects, they can be used for estimating the seismic hazard along the San Andreas fault.

5 Conclusions

From the simulations of the ground motions using the geophysical ground motion simulation model, the following results and conclusions are obtained.

1. The geophysical ground motion model can be used to estimate ground motions at a site for which limited recording data are available.
2. Consideration of the random dislocation process in time and space is necessary in order to simulated ground motions in higher frequency ranges.
3. The geophysical ground motion attenuation relationships include the characteristics of ground motions in a specific region. Since observed data for large earthquakes are very limited, the proposed model is especially useful for developing spectral attenuation relationships from large earthquake events.
4. The geophysical ground motion model for developing ground motion attenuation relationships provides an alternative to the empirical attenuation relationships developed from recorded data. Thus, the theoretical ground motions model can be applied to the large and infrequent ground motions

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