Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.VIII)

SA-8

RISK-CONSISTENT GROUND MOTIONS FROM A GEOPHYSICAL SOURCE AND SOURCE TO SITE MODEL

Shigeru Suzuki[1] and Anne S. Kiremidjian[2]

[1]Tokyo Electric Power Services Co., LTD., Chiyoda-ku, Tokyo, Japan
[2]The John A. Blume Earthquake Engineering Center, Department of Civil Engineering, Stanford University, Stanford, California, U.S.A.

SUMMARY

In this paper a theoretical ground motion simulation model is presented. The ground motion at a site is simulated using the normal mode method. A random walk model is used to represent the incoherent rupture process of the fault which is particularly important for generating the high frequency components of the ground motion. Then, the ground motion simulation model is used together with the stochastic slip-predictable model to estimate the hazard at a site. Strong earthquake ground motions are simulated for sites in Mexico City for earthquakes occurring on the subduction zone off the coast of Mexico. A good comparison is found between the recorded and simulated ground motions from the September 19, 1985 Mexico earthquake. Risk-consistent response spectra are obtained from the same simulated events that are particularly usefull for seismic design.

INTRODUCTION

In recent years, several techniques have been used to simulate earthquake ground motions. These include the ray tracing techniques (Ref. 1), elasto-dynamic Green's functions (Ref. 2), empirical Green's functions (Ref. 3) and the normal mode method (Refs. 4,5,6,7). When using ray tracing methods, it is difficult to simulate long duration and wide-band frequency waves (Ref. 1). The elasto-dynamic Green's function approach becomes difficult to apply when multilayered earth structure is considered (Ref. 2). The empirical Green's function methods are also difficult to use, because the scaling laws cannot be found in a reasonable manner (Ref. 3). High frequency waves at intermediate and far distances are difficult to generate with the normal mode method unless sufficiently large number of modes are used in the model (e.g. Refs. 4,5). The major difficulty with this approach is the long computational time required to obtain the normal modes for the earth. An important advantage of this method is that the fault rupture process and the wave propagation models can be treated separetaly. Once the eigenvalues and the eigenfunctions for the earth are evaluated, a large number of ground motions can be generated for different source-to-site distances and source parameters enabling the computation of theoretical attenuation relationships. Despite its limitations, the normal mode methods apears to be best suited for ground motion simulation and is adopted in this paper.

The theoretical ground motion model is combined with the semi-Markovian slip-predictable stochastic model (Refs. 8,9) to develop risk-consistent response spectra for various sites. For the ground motion simulation model, the rupture velocity, the asperity weights, and the patch length are assumed to be uniformly distributed random variables. The rise time, rupture time and attenuation filters are considered. Higher frequency ground motions are generated using a non-uniform fault rupture process. Ground motions were generated for Mexico City for earthquakes originating on the Mexico subduction zone. It is found that the simulated ground motions compare well with recorded ground motions from the September 19, 1985 Mexico earthquake. Risk consistent response spectra are obtained for various sites in Mexico City. Such spectra are particularly useful in seismic design code formulation.

SEMI-MARKOVIAN MODEL FOR EARTHQUAKE OCCURRENCES

In this paper, earthquake occurrences are considered to be a time dependent sequence of events that follows the slip-predictable hypothesis of Shimazaki and Nakata (Ref. 10). Based on this hypothesis, the stress released from an earthquake is proportional to the elapsed time since the last event; however, the time to the next event is random. A Markov renewal model was developed by the authors in an earlier paper to represent the time dependent behavior of earthquake sequences. This model is briefly summarized in this section and will be used in the risk-consistent response spectra computations. A more detailed discussion is given in Refs. 8 and 9.

It is assumed that there are N discrete stress levels which form the state space $E = \{1,2,\ldots,N\}$. We define the following:

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

T_n = the time of occurrence of the nth event.

Thus, the set $\{Y_n: n\geq 0\}$ are random variables assuming values in E and the set $\{T_n: n\geq 0\}$ is such that $0< T_1< T_2<\ldots$ The stochastic process $\{Y_n, T_n: n\geq 0\}$ is a Markov renewal process provided that

$$P[Y_{n+1} = j,\ T_{n+1} - T_n \leq t \mid Y_0 \ldots Y_n : T_0,\ldots T_n] = P[Y_{n+1} = j,\ T_{n+1} - T_n \leq t \mid Y_n = i] = Q(i,j,t) \quad (1)$$

for all i,j in the state space E and $t \geq 0$. In order to specify this process it is necessary to describe the one-step transition probabilities, p_{ij}, and the holding time distributions, $h'_{ij}(t)$. Both of these quantities are defined in terms of the event interarrival times which are assumed to be Weibull distributed.

Of engineering interest is the probability of exceedence of a specified level of ground motion at a site due to all possible events in some future time. In order to compute the probability of exceedence of ground motion from all possible events, we define a new state space in terms of the state space E as fallows: Let $U=\{U_1,U_2,\ldots U_N,U_{N+1},\ldots,U_{2N}\}$ where

$U_i = \{ A \leq a_0 \text{ and } Y_n = i \}$ for $i = 1,2,\ldots,N$

$U_i = \{ A > a_0 \text{ and } Y_n = i-N \}$ for $i = N+1,N+2,\ldots 2N$.

The states U_i describe the joint event that the ground motion A does not exceed level a_0 when the size of the nth event is i, for $i=1,2,\ldots N$, or that the ground motion A exceeds the level a_0 when the size of the nth event is i-N for $i = N+1,N+2,\ldots 2N$. The new process $\{X_n, T_n: n\geq 0\}$ is also a Markov renewal process assuming values in U. The transition probabilities of this process, q_{ij}, and the holding time distributions, $h_{ij}(t)$, are defined in Ref. 9.

The quantity of interest in engineering applications of the model is the probability of exceeding a specified level of ground motion a_0; that is, the probability that at least one event of size $X\geq j$ will occur in time $(t_1,t]$ given that there were no occurrences in time $(0,t_1]$ with $0<t_1<t$. That probability is given by

$$G_i(X \geq j,k \geq 1|t_1,t)= 1.0-G_i(X \geq j,k = 0,t_1|t)/H_i(t_1) \quad (2)$$

where

$$G_i(X \geq j,k = 0,t_1|t) = \sum_{r=1}^{N} \int_{t_1}^{t} q_{ir}\, h_{ir}(\tau) G_r(X \geq j,k = 0|t-\tau)d\tau +H_i(t) \quad (3)$$

and $H_i(t)$ is the complementary cumulative holding time distribution. Equations 2 and 3 were used by Kiremidjian and Suzuki (Ref. 9) with an empirical attenuation relation to obtain site hazard estimates for Mexico City. In this paper, a geophysical model is used to describe the propagation of seismic waves from the source to the site. The normal mode method and fault rupture model are presented in the following section.

THEORETICAL GROUND MOTION MODEL

The normal mode method (e.g., Ref. 11) is composed of two steps: (a) computaion of the normal modes representing the free oscillatons 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 equations of free vibrations given by

$$\|[K] - \omega^2 [M]\| = 0 \tag{4}$$

where [K] is the stiffness matrix, [M] is the consistent mass matrix and ω is the circular frequency of the earth. The eigenvalues and eigenfuncions that describe the normal modes of vibration of the earth are solutions of the homogeneous differential equation of motion. Two independent modes are identified: the torroidal modes corresponding to a twisting motion of the sphere (SH waves) and the spheroidal modes corresponding to distorting motions of the earth (P-SV waves). In computing the eigenvalues and the eigenfunctions, the sphere is considered to be radially heterogeneous and laterally homogeneous. The excitation function for computing the response motion at a site is modeled as a double-couple force. The equations for the toroidal and spheroidal modes excited by a point-source double-couple were developed by Kanamori and Cipar (Ref. 12) and are summarized in Ref. 13.

The rupture at a finite fault is modeled as a moving source. The response of the ground at a site u(x,t) some distance from the rupturing source is expressed as the convolution of the source time function S(t), the wave propagation function E(t), the attenuation function D(t), and the local soil condition function L(t). The convolution equation is given as follows:

$$u(x,t) = S(t)*E(t)*D(t)*L(t) \tag{5}$$

The Fourier transform of this equation is:

$$u(x,\omega) = S(\omega).E(\omega).D(\omega).L(\omega) \tag{6}$$

For a moving source on a fault with finite dimensions, the source spectrum can be expressed by a series of filters

$$S(\omega) = S_o(\omega).F_L(\omega).F_W(\omega).F_\tau(\omega) \tag{7}$$

where $S_o(\omega)$ is the source spectra due to a point source, $F_L(\omega)$ and $F_W(\omega)$ represent the finite length and finite width filters, respectively, and $F_\tau(\omega)$ is the finite dislocation rise time between the starting and stopping of the rupture. These filters are defined in Ref. 13. The attenuation function is given as

$$D(\omega) = e^{-\omega r/(2uQ)} \tag{8}$$

where Q is the quality factor, r is the distance from the source to the site, u is the wave velocity, and ω is the circular frequency.

The site effect function, L(t), depends on the topography and the local soil conditions. Ohsaki (Ref. 14) derived the Fourier transform of this function from one dimensional wave propagation theory as follows

$$L(\omega) = \frac{1}{\sqrt{\cos^2\frac{\omega H}{V_s} + (\alpha H)^2 \sin^2\frac{\omega H}{V_s}}} \tag{9}$$

where V_s is the shear wave velocity, H is the soil depth, $\alpha = D\omega/V_s$ and D is the damping ratio for soft soil.

Stochastic Fault Model. Currently, ground motion simulation models assume a coherent fault fupture process. In this paper, a random rupture process is described by assuming that the dislocation velocity is random in space and time. The rise time function is considered as a stationary stochastic process with a series of rectangular pulses. Each duration of the pulse, τ, is assumed to have the Poisson distribution. Then the source spectrum, $A(\omega)$, of a random rupture process in time is obtained by the Fourier transform of the autocorrelation function of the dislocation velocity time-function (Refs. 13,15). On the other hand, the source spectrum $I(\omega)$ of a random rupture process in space is obtained by assuming a distorted fault plane (Refs. 14,15). Figures 1a and 1b show schematically the uniform and random dislocation velocities in time and space respectively. Following Koyama (Ref. 14), the dislocation process is given by the random impact of particles in Brownian motion. The Fourier transform of the response ground motion at a site can be expressed as follows:

$$U(\omega) = P.A(\omega).I(\omega) \tag{10}$$

where P represents the source to site path effect, $A(\omega)$ describes the Fourier transform of the rise time function and $I(\omega)$ is the fourier transform of the spacially varying random dislocation velocity. These terms are defined in Ref. 13. The site response is obtained from the inverse Fourier transform of Eq. 10.

MODEL APPLICATION

The slip-predictable stochastic model and the theoretical ground motion model were used to estimate probabilities of ground motion at Mexico City for earthth quakes originating on the Mexico subduction zone. The parameters for the slip-predictable model are given in Ref. 9 and are not repeated here. The parameters for the ground motion model are summarized in Table 1. Most of these parameters were obtained from direct analysis of worldwide data or data for the Mexico subduction zone (see ref. 13). From sensitivity studies, it was determined that it is sufficient to simulate seismic waves in the 0 to 3 Hz frequency range and that the number of modes can be limited to 20.

Several types of results were obtained. Strong ground motions were simulated for rock and soft soil sites in Mexico City. A very good comparison was found between the time histories, Fourier spectra and response spectra from the recorded and simulated ground motions. The spectra compared particularly well in the 0 to 3 HZ frequency range. Theoretical attenuation relationships were obtained for peak ground accelerations for rock and soil sites. Figures 2a and 2b show these relationships, data from recorded strong ground motions a similar function obtained by Singh et al. (Ref. 16). The derived relationships compares well with the data and the equations proposed by Singh.

The simulated ground motions were also used to obtain risk-consistent ground motions for Mexico City. For that purpose probabilities of exceedence of spectral values were obtained at various structural periods and spectral coordinates were plotted corresponding to specified probability of exceedence levels. Figures 3a and 3b show the response spectra for rock and soil sites in Mexico City. Constant risk spectra are shown for 10% and 50% chance of exceedence.

DISCUSSION

The method for developing risk consistent response spectra described in this paper has several advantages over existing approaches. Ground motions can be simulated for regions for which the strong motions recording data are too small to develop empirical attenuation functions. Furthermore, entire time histories are obtained thus parameters other than peak ground acceleration can be used for hazard analysis. The main limitations of the model are the long computational time required to obtain the normal modes for the earth, the large number of modes needed for obtaining the higher frequency waves and difficulties with determining the seismic source parameters. With the increased computaional capacity of computers, the long computational time and the large number of modes do not present a major obstacle. Source parameters are considerably more difficult to determine, however, for most active seismic regions such data are continuously being developed.

ACKNOWLEDGEMENT

This research was partially supported by the U.S. National Science Foundation ECE Grant -86-10867 and by the Tokyo Electric Power Services Co., LTD, Tokyo, Japan.

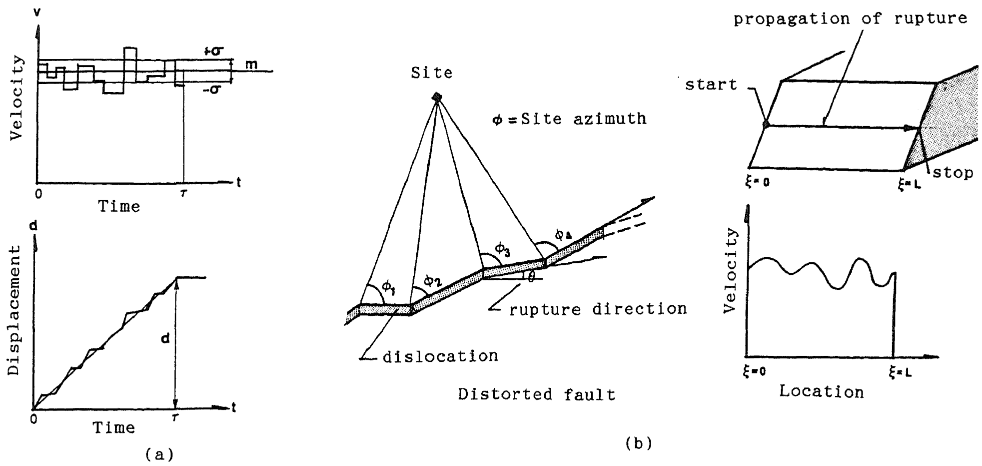

Fig.1 Non-uniform Velocity (a) in time (b) in space

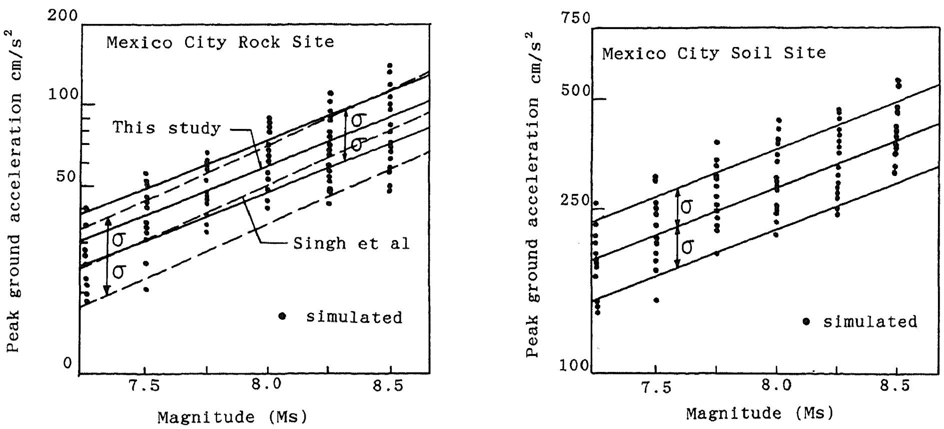

Fig.2 Theoretical Attenuation relations

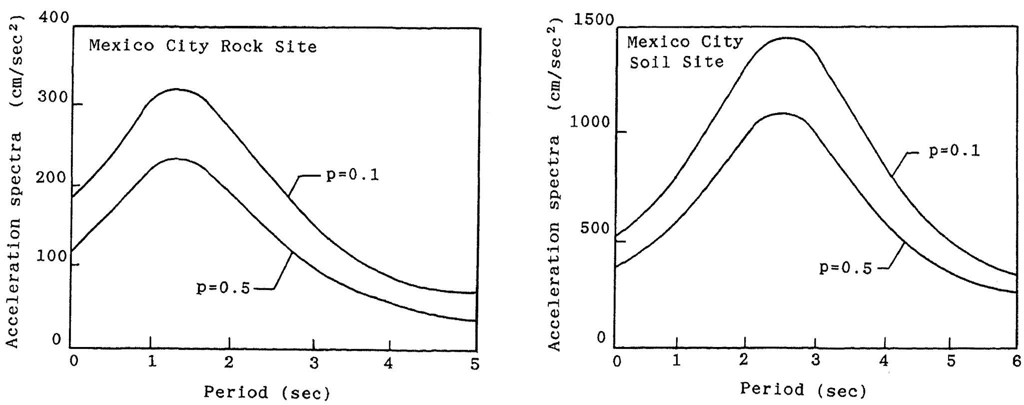

Fig.3 Risk-consistent Response Spectra for Mexico City

Table 1
List of Source Parameters and Their Distributions

Parameters	Type of Distribution	Scaling Law	Database
Seismic Moment	Normal Distribution	$\log M_o = 1.1M_s+19.03$	Middle America Tren
Fault Dimension	Normal Distribution	$\log L = 0.33M_s-0.62$	Middle America Tren
Fault Geometry	Normal Distribution	No	Middle America Tren
Rise Time	Normal Distribution	$\tau = 0.49\sqrt{M_s}+2.53$	World Wide
Rupture Velocity	Uniform Distribution	No	World Wide
Patch Length	Normal Distribution	$\log \rho = 0.55M_s-3.27$	World Wide
Quality Factor	Constant	No	Middle America Tren
Earth Structure	Constant	No	Middle America Tren
Soil Parameter	Normal Distribution	No	Mexico City
Strain Energy Rel. Dist. on a fault	Uniform Distribution	No	
Weighting factor	Uniform Distribution	$0.75 < e < 1.25$	

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