SPECTRAL CHARACTERISTICS OF EARTHQUAKE GROUND MOTION MODEL WITH CONSIDERATION OF UNCERTAIN SOIL PROPERTIES AND SOURCE MECHANISMS

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SUMMARY

This paper presents the earthquake ground motion model considering the seismic radiation from the random source moving with a constant rupture velocity in a semi-infinite random medium. The analyses of wave form functions, spectral characteristics and energy envelope functions of it suggest that the rupture velocity, rupture directivity and ratio of epicentral distance to focal depth are important factors for aseismic design of structural systems at the site especially in the near-field.

INTRODUCTION

The mathematical earthquake ground motion model with consideration of unspecified source movement and geological property from source-to-site has recently become effective tool to estimate the synthetic seismogram for the actual earthquake record. However, the multiple reflection and refraction of traveling wave motion due to the irregular properties of transmission path and rupture process such as nucleation of rock failure and rapid spreading of the stresses accumulated in the source region give the spatial and time fluctuations on the characteristics of an earthquake.

In relation to the above statement, the problem of radiation intensity of seismic wave motion propagating in an elastic continuous random medium is examined by applying the smoothing approximation method (Ref. 1).

On the other hand, the rupture process which characterizes a high frequency content relating to the nonuniform distribution of various physical properties on the fault plane is represented by the kinematic source model with the five parameters; the fault length; the fault width; the rupture velocity; the average offset; the rise time (Ref. 2).

In this paper, the earthquake ground motion model is generated by convolution of the Green's function of a semi-infinite random medium and the random source time function which shows outling some general properties of the five parameter source model on the assumption that the occurrence of nucleation of rock failure obeys the counting process. Moreover, average response spectra, energy envelope functions and evolutionary power spectra of it are analyzed to obtain some indications of the influence rupture velocity, rupture directivity and relative position between the seismic focus and the observation points have on aseismic design of structural systems.

SEISMIC SOURCE MODEL AND EARTHQUAKE GROUND MOTION MODEL

The dislocation on a fault plane may be modeled as the sum of intensity

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functions to the subevents occurring on the individual segment which is derived by dividing the fault surface into some elements. If the rupture triggers the subevents at random instants $0<t_{j1}<t_{j2}<\ldots<t_{jNM(t)}$, $(j=1,\ldots,M)$, the ensemble of random earthquake ground motion model $Y_D(p;t)$ is obtained by superposition of pulse shape functions emitted from dislocation over the entire fault plane as follows;

$$Y_D(p;t)=\sum_{i=1}^{M}\int_{0}^{t} G_D(p;t-t')n_i(t')u_i(t') \quad , \quad \begin{matrix} D=(z,r,\phi) \\ p=(0,r,\phi) \end{matrix}$$

$$u_i(t)=\sum_{j=1}^{Ni(t)}\delta(t-t_{ij})dt \qquad (1)$$

where $G_D(p;t)$, $n_i(t)$ and $Ni(t)$ are the nondimensional average Green's function of a semi-infinite random medium for point source (Ref. 1), the intensity function of the ith segment and the total number of the subevents occurring at the ith segment in time interval $(0,t)$. The suffix $D=(z,r,\phi)$ indicates the vertical, radial and cross-radial components. $u_i(t)$ is the counting process which represents the cumulative number of emissions of intensity function in time interval $(t,t+dt)$ at the ith segment. Since the dislocation propagates with rupture velocity v_r, the intensity function of eq.(1) is represented for simplicity to be

$$n_i(t)=\frac{C_0M_0}{Wt_rL_0}\left(t-\frac{r_i}{v_r}\right)\left\{ H\left(t-\frac{r_i}{v_r}\right)-H\left(t-t_r-\frac{r_i}{v_r}\right) \right\} \qquad (2)$$

in which W, t_r, L_0, M_0, C_0 and M indicate width of fault, rise time, reference of source force, seismic moment, coefficient derived from dislocation theory and the number of the segments. $\delta(t)$ in eq.(1) and $H(t)$ in eq.(2) are Dirac's delta function and Heaviside step function, respectively.

Earthquake time histories of eq.(1) are calculated for Mach numbers $Mn=0.7$ and 0.9 and nondimensional rise time $t_r=0.03$. We assume that the rupture front propagates in the forward and backward directions as shown Fig.1 which shows the geometric relation between the causative fault and the observation points. Here, the faulting process is furthermore simplified by considering that the subevents occure at a finite number of source points on the fault line CD. A uniform distribution is assumed to describe the probability of occurrence of the subevents for simplicity and the selected number M is 25.

Figs.2 and 3 show the wave form functions of the ground motion model for the ratio of epicentral distance to focal depth $R/H=1$ when the rupture front propagates in the forward and backward directions. For the forward fault movement, P and SV wave motions radiated along the fault line from starting point C to ending point D are superposed at almost the same time in vertical and radial components, and the peak accelerations of them increase especially when Mn increases. Since the observation point of cross-radial component is almost perpendicular to the fault movement as shown in Fig.1, the peak accelerations of the component are not so variable with Mn as those of vertical and radial components. For the backward fault movement, the difference in travel times from the two source points to the observation points of vertical and radial components plus the original time interval of occurrence of the subevents, and the peak accelerations of them are generally smaller than those for the forward fault movement.

In Fig.4, the wave form functions corresponding to Figs.2(a) and 3(a) are shown for R/H=5. Since vertical and radial components consist of P,SP,SV and Rayleigh wave motions, wave form functions of them are more complicated than those for R/H=1. There being some differences in the propagation velocities among *P*, *SV* and *Rayleigh* wave motions, the duration time of an earthquake becomes inevitably long with increase of R/H. From the fact that the peak accelerations of the ground motion model for R/H=5 are less sensitive to Mach number than those for R/H=1, the stochastic characteristics of them tend gradually to be stationary as seismic wave motion propagates into the far-field.

AVERAGE RESPONSE SPECTRA DUE TO EARTHQUAKE GROUND MOTION MODEL

The linear and nonlinear responses of the earthquake ground motion model would be effective in estimating the safety and reliability of structural systems based on seismic microzoning.

Figs.5 and 6 show average response spectra of displacement, velocity and acceleration of radial component for R/H=1 when the rupture front propagates in the forward and backward directions. Three solid lines in the figures denote the spectra for the critical damping ratios h_0=0.0, 0.01 and 0.05, respectively. The responses in these figures become large significantly due to up-Doppler effect associated with fault movement especially when Mn increases. Since the peaks of responses for the backward fault movement move in the lower period range due to down-Doppler effect, they are smaller than those for the forward fault movement.

In Fig.7, the response spectra for R/H=5 corresponding to Figs.5(a) and 6(a) are shown. They draw relatively flat shape along period comparing those for R/H=1. Although the earthquake allows generally the influence of rupture velocity, there are not so much difference among the characteristics of response spectra of R/H=5 for the both forward and backward fault movements even if the absolute values of them are different each other.

TIME-VARIANT ENERGY ENVELOPE FUNCTION OF EARTHQUAKE GROUND MOTION MODEL

The irregular earthquake ground motion has been idealized in the form of nonstationary stochsatic process which is described by the two physical quantities with respect to the time variation of intensity level and spectral characteristics. Here, the nonstationarity of the earthquake ground motion model is examined by means of the concept of energy envelope function. The energy envelope function $E_D(p;t)$ is defined as the finite time-averaged variance of the output process through a band pass filter W(t) by the following form;

$$E_D(p;t)=\frac{1}{2T}\int_{-T}^{T} W(t-t')Y_D^2(p;t')dt' \tag{3}$$

For the triangular and rectangular weighting functions, eq.(3) is expressed approximately by

$$E_D(p;n)=\sum_{j=1}^{N}\delta_{n,j}\frac{1}{2T}\int_{-T+n}^{T+n} W(g)Y_D^2(p;n-g)dg \tag{4}$$

$$= \sum_{j=1}^{N} \delta_{n,j} \left\{ \sum_{k=-L+n}^{L} {}_{k}Y_{D}^{2}(k)W(n-k) \right\} \left(\frac{1}{2L+1} \right) \quad , \quad T=LdT$$

In eqs.(3) and (4), T, dT, N and $\delta i,j$ are time length of weighting function, sampling time, number of sampling in time interval (0,T) and Kronecker's delta, respectively.

Figs.8, 9 and 10 show the energy envelope functions of the ground motion model for triangular and rectangular weighting functions with soild and dotted lines, respectively. They are normalized by their maximum values. The time length of those weighting functions is taken to be 1/5 of duration time of the ground motion motion model.

The energy envelope functions seem to be similar to those idealized from the observed earthquakes by Iyengar (Ref. 3) and Shinozuka (Ref. 4). The time -dependent variation of those functions indicates the nonstationarity of the earthquake ground motion model though a uniform distribution is assumed for the probability of occurrence of the subevents on the segments. Therefore, the nonstationarity of intensity level of an earthquake may mainly depend on the spatial variation of magnitude of seismic wave motions coming from the different segments in the fault plane. It is also found that the up-and down-Doppler effect associated with fault movement produces some differences on the nonstationarity of the ground motion model.

There are two peaks in the envelope function of vertical component for R/H=5, which are formed by the portions of P and SP wave motions and SV and Rayleigh wave motions of the ground motion model. Such peaks are frequently seen in the energy envelope functions of the actual earthquakes.

From all the energy envelope functions of the earthquake ground motion model analyzed, most weak nonstationarity of intensity level is shown for the case that the rupture front propagates in the backward direction and the ratio of epicentral distance to focal depth is 5.

EVOLUTIONARY POWER SPECTRA OF EARTHQUAKE GROUND MOTION MODEL

It is important to find the efficient method of spectral analysis for study of spatial and time variant-characteristics of an earthquake ground motion due to the irregular geological properties of transmission path and faulting process. The evolutionary power spectrum, which describes the local power frequency distribution at each instant of time for the nonstationary process, has possibility to evaluate the time process of dislocation in a source region and the heterogeneous crustal structures from source-to-site.

Although there are many mathematical definition of power spectra for the nonstationary process, the evolutionary power spectrum $S_D(\omega,t)$ is defined for simplicity by the following form (Ref. 5);

$$S_D(\omega,t) = \frac{2h_0\omega_0^3}{\pi} \left(\sigma_x^2 + \frac{\sigma_{\dot{x}}^2}{\omega_0^2} \right) \tag{5}$$

where ω_0, σ_x and $\sigma_{\dot{x}}$ indicate the natural frequency of a narrow band filter, the standard deviations of displacement and velocity of it.

In Figs.11 and 12, the evolutionary power spectra of radial component of the ground motion model corresponding to Figs.5 and 6 are shown along time with nondimensional period. The peaks of them move to higher and lower period range in accordance with the up-and down-Doppler effect of the fault movement.

They have several peaks for the period and time relating to the specific time interval between the nucleation and stopping of the subevent on the fault line, and the evolutionary power spectrum will be useful means to know the characteristics of wave traveling path and faulting process if the estimation of them is possible for many earthquakes systematically obtained by multi-observation point system.

CONCLUDING REMARKS

The earthquake ground motion model considering the seismic radiation from the moving random source model in a semi-infinite random medium is presented to investigate the relationship between the causative factors of an earthquake and the important physical quantities of aseismic design of structural systems.

According to the numerical analyses of the earthquake ground motion model, there is a strong dependence of peak acceleration, frequency content, duration time, average response spectra, energy envelope functions and evolutionary power spectra of it at the site in the near-field on the rupture direction of dislocation and relative position between the focus of an earthquake and the observation point. Especially they show significant variation due to up-and down-Doppler effect associated with fault movement.

From the examination of energy envelope functions of the earthquake ground motion model, they are similar to those idealized from the observed earthquakes by Iyengar and Shinozuka. Then, the nonstationarity of the intensity level of an earthquake may be mainly produced by the spatial variation of magnitude of seismic wave motion which is described from the relative position between the moving source and the observation point.

The evolutionary power spectrum represents the local power frequency distribution at each instant of time for the nonstationary process, and it will be efficient means for estimation of the field attenuation in propagation path and faulting process on the basis of multi-observation point system for the activities of many earthquakes.

Since the peak accelerations, response spectra and energy envelope functions of the earthquake ground motion model for R/H=5 are less sensitive to Mn than those for R/H=1, the stochastic characteristics of them tend gradually to be stationary as seismic wave motion propagates into the far-field.

Although the earthquake ground motion model presented here is provided by a rough frame work for modeling and interpreting an earthquake, it will be developed to the more efficient one in predictably estimating response characteristics of structural systems for future earthquake by improvement of source model and accurate estimation of field attenuation of transmission path.

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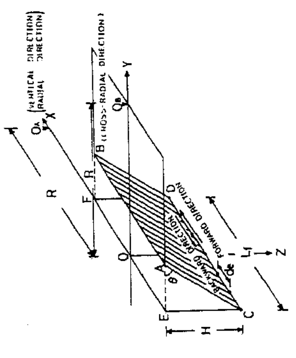
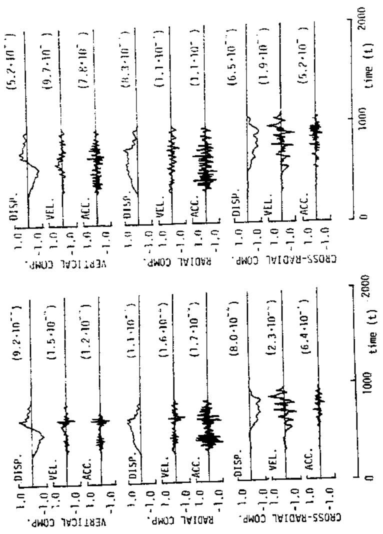
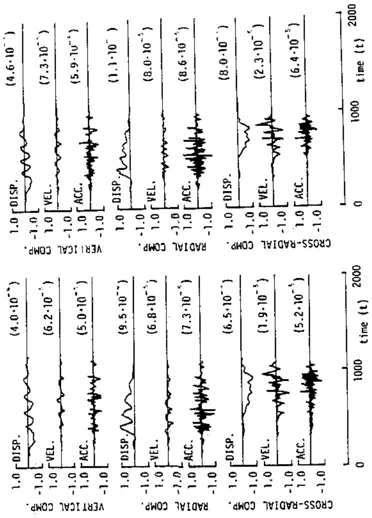


Fig. 1 Geometric relation between causative fault and observation point



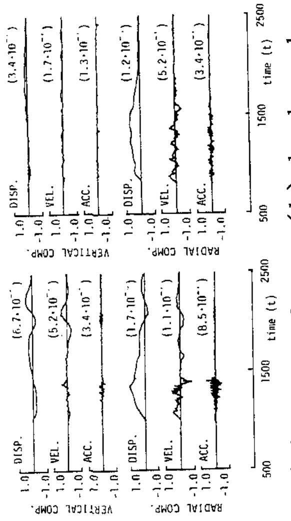
(a) Mn=0.7 (b) Mn=0.9
(forward direction)

Fig. 2 Wave form function
(R/H=1)



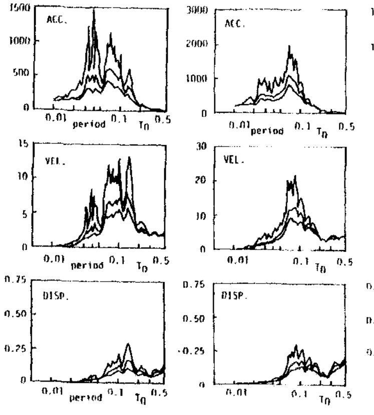
(a) Mn=0.7 (b) Mn=0.9
(backward direction)

Fig. 3 Wave form function
(R/H=1)

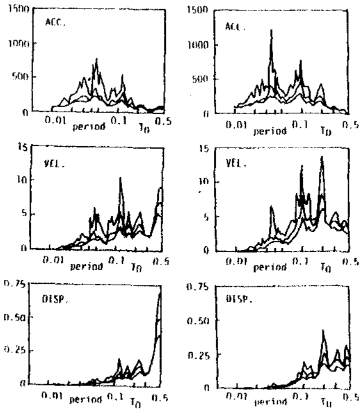


(a) forward direction (b) backward direction

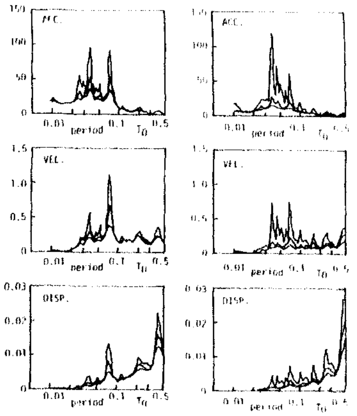
Fig. 4 Wave form function
(R/H=5, Mn=0.7)



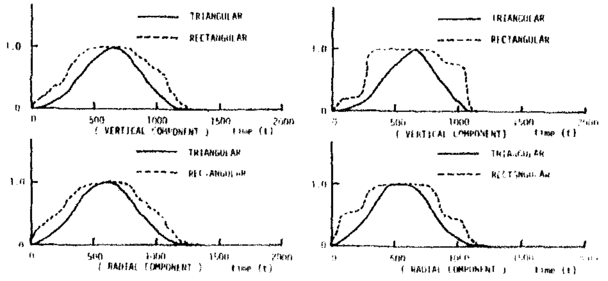
(a) Mn=0.7 (b) Mn=0.9
(forward direction)
Fig. 5 Average response spectrum (R/H=1)



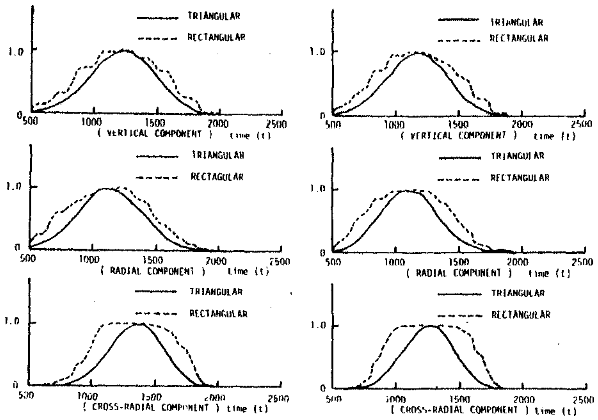
(a) Mn=0.7 (b) Mn=0.9
(backward direction)
Fig. 6 Average response spectrum (R/H=1)



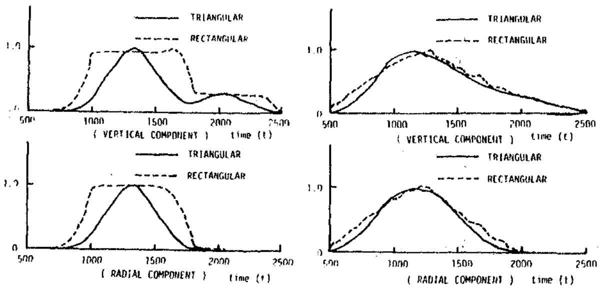
(a) forward direction (b) backward direction
Fig. 7 Average response spectrum
(R/H=5, Mn=0.7)



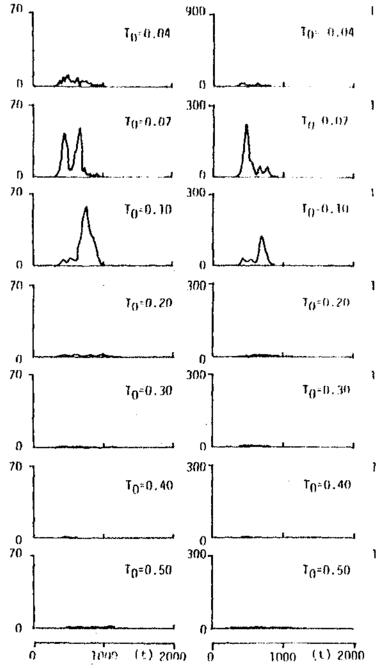
(a) Mn=0.7 (b) Mn=0.9
(forward direction)
Fig. 8 Energy envelope function (R/H=1)



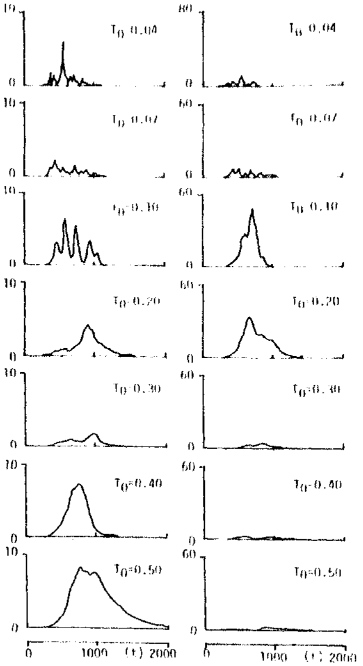
(a) Mn=0.7 (b) Mn=0.9
(backward direction)
Fig. 9 Energy envelope function (R/H=1)



(a) forward direction (b) backward direction
Fig. 10 Energy envelope function
(R/H=5, Mn=0.7)



(a) Mn=0.7 (b) Mn=0.9
(forward direction)
Fig. 11 Evolutionary power spectrum (R/H=1)



(a) Mn=0.7 (b) Mn=0.9
(backward direction)
Fig. 12 Evolutionary power spectrum (R/H=1)