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SIMULATION OF RISK-CONSISTENT EARTHQUAKE MOTION

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SUMMARY

A method is developed to combine probabilistic seismic hazard analysis and stochastic earthquake motion models. A set of parameters characterizing stochastic earthquake motion models are determined on a consistent probabilistic basis. The method proposed herein consists of two steps. First, the ground motion intensity is determined in the context of the conventional hazard curve technique. Next, other ground motion parameters are determined as conditional means corresponding to the annual probability of exceedance for the ground motion intensity. Simulated ground motions using the procedure developed herein are called "risk-consistent earthquake motion." Some numerical application are presented.

INTRODUCTION

In the presence of various sources of uncertainty in seismic activities and ground motions, probabilistic methods provide a powerful means for seismic load estimation. A standard method is probabilistic seismic hazard analysis[1)], which will determine the relation between an earthquake motion intensity (PGA, PGV, response spectra, etc.) and corresponding annual probability of occurrence (or return period), the graph representing this relation being called hazard curves.

Application of stochastic earthquake motion models requires simultaneous determination of several model parameters such as rms intensity, predominant frequency, duration, spectral shape parameter, etc. This is beyond the scope of conventional seismic hazard technique which can handle only a single ground motion intensity parameter. Exact application of probability concepts involves joint probability distribution of these parameters, and will cause excessive analytical complication.

This study presents a method that will determine stochastic earthquake motion model parameters on a consistent probabilistic basis. It is compatible with the conventional hazard curve method, and provides a simple method for determining other parameters without dealing with complex multi-dimensional probability space.

PROBABILISTIC DETERMINATION OF A SET OF GROUND MOTION MODEL PARAMETERS

Basic Concept. The method proposed herein presumes all parameters characterizing the stochastic ground motion model are defined as functions of earthquake magnitude and distance.

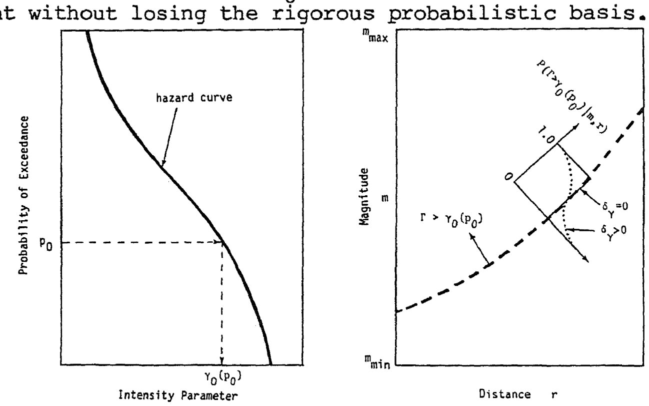
It is also noted the ground motion intensity is more important than any other parameter such as duration, predominant frequency, spectral shape parameter, etc. With this notion, the intensity parameter is determined on the basis of rigorous application of probabilistic seismic hazard analysis. Its result is given in the form of the hazard curve [Fig.1(a)], which gives the relation between the annual probability of exceedance p_0 and the corresponding intensity level $\gamma_0(p_0)$.

The remaining model parameters are determined under the condition that we are dealing with a set of earthquakes such that the site intensity caused by them exceeds $\gamma_0(p_0)$: i.e. $\Gamma > \gamma_0(p_0)$. The concept is illustrated schematically in Fig.1(b), showing the conditional probability of $\Gamma > \gamma_0(p_0)$ for given values of magnitude and distance, m and r, respectively. Herein $\delta\gamma$ denotes the coefficient of variation of attenuation uncertainty. When $\delta\gamma=0$, one can draw a definite border line in Fig.1(b) dividing the area where $P(\Gamma > \gamma_0(p_0)|m,r)=1$ and that where $P(\Gamma > \gamma_0(p_0)|m,r)=0$. It is shown by a dashed line : it defines a subset of earthquakes such that $\Gamma > \gamma_0(p_0)$. When $\delta\gamma>0$, the conditional probability $P(\Gamma > \gamma_0(p_0)|m,r)$ varies continuously as the dotted line. On this account, the model parameters, typically denoted by x, other than the intensity parameter, are determined from

$$\bar{X}(p_0)=E[x|\Gamma > \gamma_0(p_0)] \tag{1}$$

where the probability $P(\Gamma > \gamma_0(p_0))$ takes the role of a weighting function in determination of the conditional mean.

In this manner, all ground motion model parameters are determined as function of a single risk parameter p_0. This enables one to enjoy the simplicity of the treatment without losing the rigorous probabilistic basis.



(a) Intensity Parameter

(b) Conditional Probability Space of M And R under A Given Value of p_0

Fig.1 Determination of Ground Motion Parameters

Determination of the Intensity Parameter Conventional seismic hazard model assuming random and independent occurrences of earthquakes is used. The annual probability that the random intensity Γ at a specific site will exceed a value γ is represented by

$$p_0=1-\exp\left\{-\sum_{k=1}^{n}\nu_k q_k(\gamma)\right\}\cong\sum_{k=1}^{n}\nu_k q_k(\gamma) \tag{2}$$

in which n=number of potential earthquake sources in the region of the site, ν_k=earthquake occurrence rate in source k with upper and lower bound magnitudes m_{uk} and m_{lk}, respectively, and $q_k(\gamma)$ represents the probability of $\Gamma>\gamma$ given that an earthquake occurs in source k ; i.e.,

$$q_k(\gamma)=\int_{m_{lk}}^{m_{uk}}\int_{r_{lk}}^{r_{uk}}P(\Gamma>\gamma|m,r)f_{Mk}(m)f_{Rk}(r)\mathrm{d}m\mathrm{d}r \tag{3}$$

where $f_{Mk}(m)$=probability density function of magnitude M in source k, $f_{Rk}(r)$=probability density function of distance R (upper and lower value=r_{uk} and r_{lk}) in source k and $P(\Gamma>\gamma|m,r)$=probability of $\Gamma>\gamma$ for given m and r.

Then the hazard curve is obtained by calculating p_0 from Eq.(2) for various values of $\delta\gamma$, allowing one to determine the value of the intensity parameter $\gamma_0(p_0)$ corresponding to a specified value of p_0, as shown in Fig.1(a).

Determination of Remaining Ground Motion Parameters For a specified value of p_0, the remaining ground motion parameters are determined on the basis of Eq.(1). Let X represent any model parameter being discussed. Assume that it is represented as a function of the earthquake magnitude m and distance r ; i.e.,

$$X = g(m,r) \tag{4}$$

The conditional mean of x for the source k, given that $\Gamma > \gamma_0(p_0)$ is obtained as follows :

$$\begin{aligned}\overline{X}_k(P_0) &= E[X|\Gamma > \gamma_0(p_0) \cap E_k] \\ &= \int_M \int_R g(m,r) f_{M,R|\Gamma > \gamma_0(p_0)}(m,r)\,\mathrm{d}r\mathrm{d}m \\ &= \frac{1}{q_k(\gamma_0)} \int_M \int_R g(m,r) P(\Gamma > \gamma_0(p_0)) f_{Mk}(m) f_{Rk}(r)\,\mathrm{d}r\mathrm{d}m\end{aligned} \tag{5}$$

where E_k represents an event that an earthquake occurs in the source k, and $f_{M,R|\Gamma>\gamma_0(p_0)}(m,r)$ represents the conditional joint probability density function of the magnitude and the distance, given that $\Gamma > \gamma_0(p_0)$. When all potential earthquake sources are considered, the conditional mean of X is represented by

$$\overline{X}(p_0) = \frac{\sum_{k=1}^{n} \overline{X}_k(p_0) \nu_k q_k(\gamma_0)}{\sum_{k=1}^{n} \nu_k q_k(\gamma_0)} \tag{6}$$

Hazard-Consistent Magnitude and Distance The conditional mean of the magnitude $\overline{m}(p_0)$ and that of the distance $\overline{r}(p_0)$, obtained from Eq.(6) by replacing x by m or r, are called herein the hazard-consistent magnitude and the hazard-consistent distance, respectively.

They give us a definite picture of the overall characteristics of earthquakes that realize the event $\Gamma > \gamma_0(p_0)$ for a prescribed value of p_0. Besides, the ground motion model parameters can be determined approximately by substituting $\overline{m}(p_0)$ and $\overline{r}(p_0)$ for m and r in Eq.(4) ; i.e.,

$$\overline{X}(p_0) \cong g(\bar{m}(p_0), \bar{r}(p_0)) \tag{7}$$

Detailed discussion of their concept is presented elsewhere (Ref.2).

GENERATION OF RISK-CONSISTENT EARTHQUAKE MOTION

All the ground motion model parameters can be determined to be consistent with the risk parameter p_0 using the method proposed in the preceding chapter. If sample ground motions are generated by using the model parameters determined in this way, such ground motions may be called 'risk-consistent earthquake motions.' On this basis, risk-consistent earthquake motions are generated by using a stochastic ground motion model.

Stochastic Earthquake Ground Motion Model Used in This Study Sugito and Kameda (Ref.3) proposed a non-stationary earthquake motion prediction model on free rock surface, where the baserocks with shear wave velocity over 600-700 m/sec. The model used herein, amplitude modulated process model[4] EMP-IBRA, is based on that in Ref.3, but the spectral function is represented by rational function.

The evolutionary spectrum for EMP-IBRA is determined by the following four parameters : peak rms intensity γ, time for the maximum value of the evolutionary spectrum t_m, predominant frequency f_{p0} and spectral shape parameter β_{g0}.

Fig.2(a)-(d) show the values of these model parameters for various values of magnitude and epicentral distance. In the epicentral region defined as[5] $\Delta < \Delta_0 = 1.06*10^{0.242m}$(in km), the ground motion intensity is assumed to be uniform ; i.e., all parameters within Δ_0 are determined with $\Delta = \Delta_0$.

Moreover, the effect of non-linear soil amplification is incorporated by using conversion factor[4] β_R which is also represented by a rational function. Thus earthquake ground motions with arbitrary site condition can be calculated.

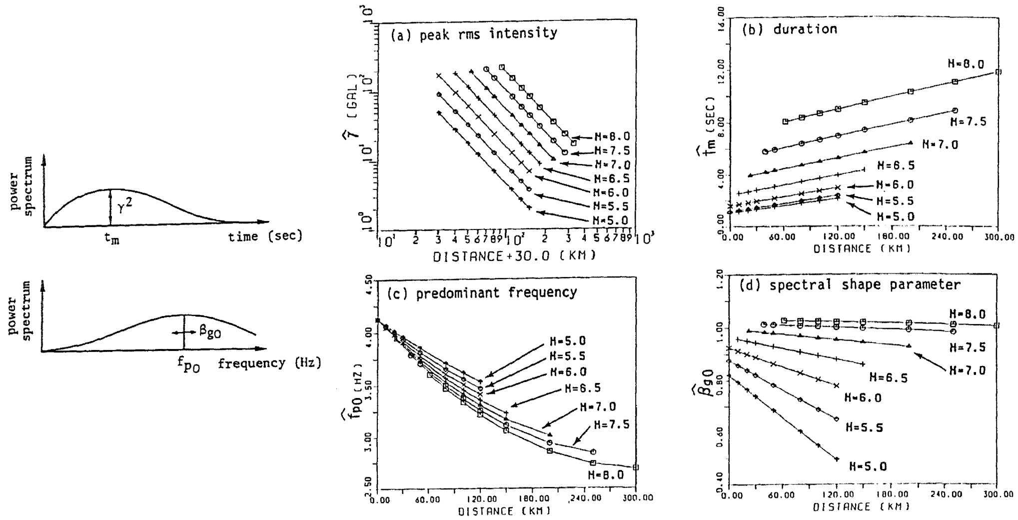


Fig.2 The values of Model Parameters

<u>Determination of Model Parameters</u> Two locations, Tokyo and Osaka, were selected for the sites for illustrative examples. The earthquakes under consideration are those that occurred within 300km of the respective sites.

(1) Hazard curves for determination of peak rms intensity

Hazard curves of peak rms intensity γ for various values of are shown in Fig.3. Kameda and Sugito[6] proposed $\delta\gamma$=0.427 as the level of remaining attenuation uncertainty after site condition is considered. The values of p_0 for Tokyo are always larger than those for Osaka for the same value of $\delta\gamma$. This comes from the difference in the average occurrence rate. In the case where $\delta\gamma$=0, the maximum value of γ is limited to about 220gal because of the upper bound determined for epicentral regions.

(2) Hazard-consistent magnitude and epicentral distance

Fig.6 shows the hazard-consistent magnitude $\bar{m}(p_0)$ and epicentral distance $\bar{r}(p_0)$. It is observed that $\bar{m}(p_0)$ increases with decreasing p_0. This result is due to considering rare events in the distribution of magnitude. For the same reason, the values of $\bar{r}(p_0)$ generally decreases with decreasing p_0. An exceptional case is observed in Tokyo with $\delta\gamma$=0 and p_0<0.01, where $\bar{r}(p_0)$ increase with decreasing p_0. The reason for this is explained as follows. Such a level of ground motion intensity can occur only in the case where m>7.5 because of the upper bound of intensity parameter determined for epicentral regions (see Fig.2(a)). Besides, earthquakes whose magnitudes exceed 7.5 give uniform ground motion intensity within epicentral regions Δ_0(m) whose size increases with increasing magnitude. As a consequence, the value of hazard-consistent epicentral distance increases with decreasing p_0.

(3) Exact and approximate values of duration, predominant frequency, and spectral shape parameter

The values of duration $\overline{t_m}(p0)$, predominant frequency $\overline{f_{p0}}(p_0)$, and spectral shape parameter $\beta_{g0}(p_0)$ are shown by the solid lines in Fig.7. These results are consistent with the variation of the hazard-consistent magnitude and distance.

Approximate values for the risk-consistent ground motion model parameters obtained from Eq.(7) are shown by dashed lines in Fig.5. Observe that they are in good agreement with the exact values.

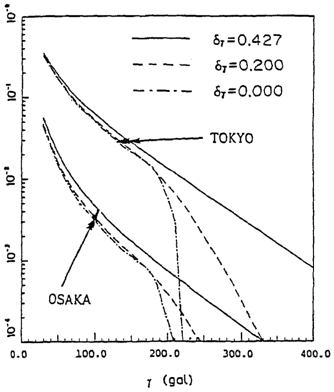


Fig.3 Hazard Curves for Tokyo and Osaka

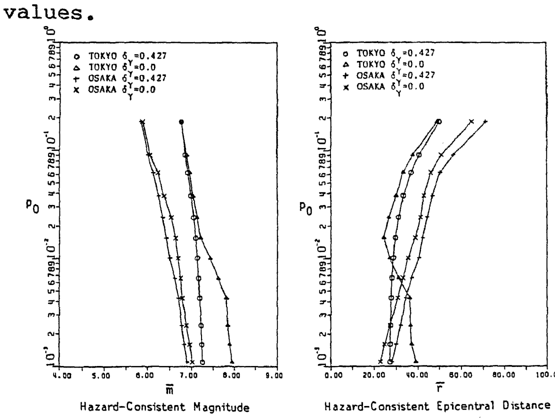


Fig.4 Hazard-Consistent Magnitude and Epicentral Distance

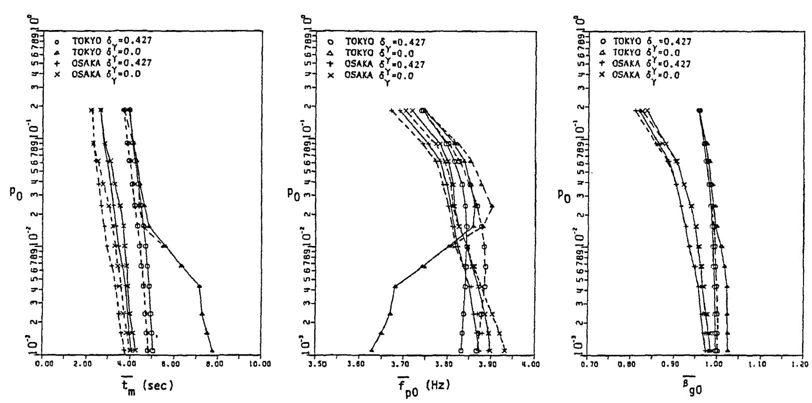


Fig.5 Conditional Means of Model Parameters (——— exact;, ----- approximate)

Generated Risk-Consistent Earthquake Motion With the values of model parameters calculated as above, simulated ground motion can be generated for given p_0 and given soil condition. Only soil surface motion using EMP-IBRA are shown in Fig.6. These are the cases for p_0=0.02 and 0.005 (return period T_r=50 and 200 years, respectively) and $\delta\gamma$=0. Both of the ground conditions are the usual alluvial deposits. Differences in values of the model parameters between Tokyo and Osaka appear especially in the PGA and in the length of duration.

However, this model deals with body waves only, and does not incorporate surface waves. This has caused lack of predominant long period components in the displacement time histories in Fig.6. When the effect of surface waves is of engineering concern, further consideration should be made.

CONCLUSIONS

Major conclusions derived from this study may be summarized as follows.

(1) A method to combine probabilistic seismic hazard analysis and stochastic earthquake motion models is presented, where a set of ground motion model parameters is determined from a single index p_0, the annual probability of exceedance for the value of the intensity parameter.

(2) The concept of the hazard-consistent magnitude and the hazard-consistent distance can be used as a convenient tool for determinating the set of ground motion parameters in a simple manner.
(3) On the basis of the method developed herein, 'risk-consistent ground motion' has been generated for some cases.

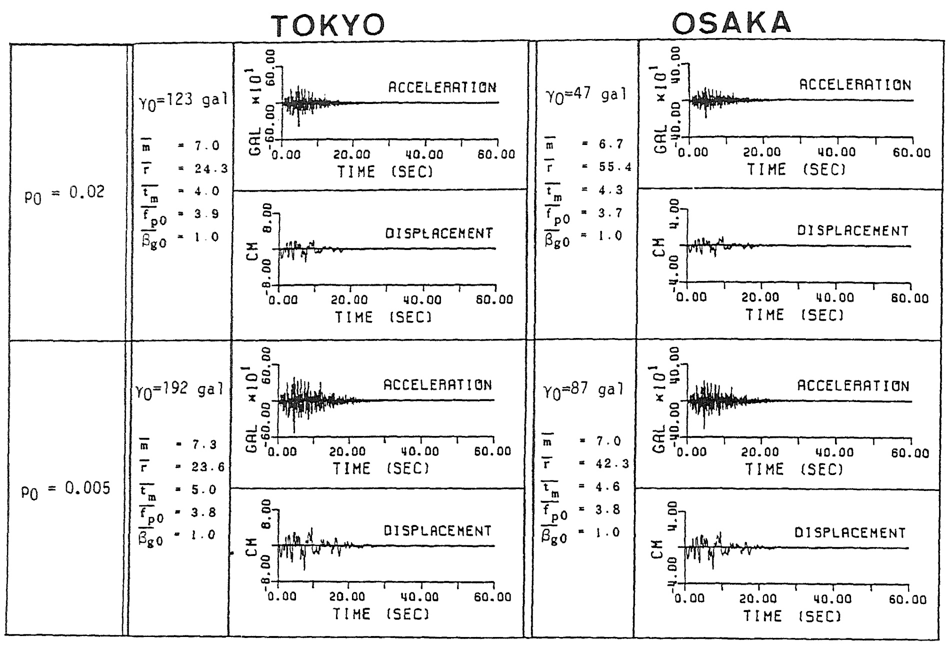


Fig.6 Examples of Risk-Consistent Earthquake Motions for Tokyo and Osaka

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