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

3-3-16

MODELING NONLINEAR SOIL AMPLIFICATION OF EARTHQUAKE MOTION WITH APPLICATION TO RANDOM STRUCTURAL RESPONSE

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SUMMARY

A simple method is developed for conversion between soil surface and rock surface ground motion including nonlinear amplification effect of soil layers overlying bedrocks. The conversion factor β is defined for peak ground acceleration, velocity, and spectral ground motion parameters. Based on the conversion factor for spectral parameters and the rock surface earthquake motion prediction model, the method is extended to the closed form random vibration solution of probabilistic response spectra both on rock and soil surface for given magnitude, distance, and local soil conditions.

INTRODUCTION

The amplification effect of soil layers over bedrock on ground motion intensity is generally remarkable and has been observed in the earthquake records. Since most of the data were those for relatively weak earthquakes, the discussion have been mainly focused on the constant amplification ratio due to the soil conditions. However, in an engineering point of view, the nonlinear amplification effect of soil layers in the case of the strong ground motion is of special importance.

In this view of the problem this study presents the conversion factor, β, which converts the peak ground motion, and the spectral ground motion parameters from rock surface level to soil surface level incorporating nonlinear amplification effect of soil layers. The conversion technique is extended to the application to the closed form random vibration solution of probabilistic response spectra on the basis of the earthquake motion prediction model developed by the authors.

CONVERSION FACTOR BETWEEN EARTHQUAKE MOTION ON ROCK SURFACE AND SOIL SURFACE

Definition of Conversion Factor β (Ref.1) Let Y_s and Y_r represent the ground motion intensity on soil surface and rock surface, respectively. Herein, the rock surface with the shear velocity v_s=600~700 m/sec is dealt with, where the design spectra for significant structures including nuclear power plants have been proposed. These ground motion intensities are related by the conversion factor as follows.

$$Y_s=\beta\cdot Y_r, \qquad \beta=\beta(S_n, d_p, Y_r) \tag{1}$$

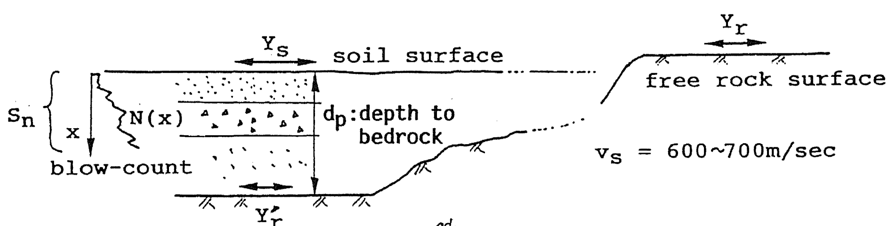
where β is the conversion factor defined by the two typical soil parameters S_n, d_p and the ground motion intensity Y_r on rock surface. The soil parameter S_n represents the softness of surface ground and is given from the blow-count profile obtained from the standard penetration test. The definition of S_n is shown in Fig.1. In

Eq.(2) in Fog.1, $N_x(x)$=blow-count at depth x meters and d_s=depth of the blow-count profile. The numerals in Eq.(2) have been obtained statistically under the condition that the parameter S_n represents the effect of the softness of surface layers on peak ground motion. The other parameter d_p is the depth of soil surface to bedrock(Ref.3).

In Eq.(1), the ground motion intensity Y_r on rock surface is necessary to incorporate the nonlinear amplification characteristics depending on the level of input motion into the conversion factor. Fig.1 shows the schematic description for these ground motion parameters.

Modeling of Conversion Factor for Peak Ground Motion For the modeling of conversion factor, the simulated ground motion both for rock surface and soil surface are used. The nonstationary earthquake motion prediction model for rock surface(EMP-IB)(Ref.4) is used for generation of rock surface motion for various combinations of earthquake magnitude and epicentral distance. The corresponding soil surface motions for typical Japanese strong motion observation stations, where the soil profile data to the bedrock are available, are calculated. In this procedure the input motion to the bedrock are obtained from the rock surface motion by multiplying them by 1/2, and the equi-linearized method have been used.

Table 1 gives the results for the formulas for the calculation of the conversion factors β_a and β_v for peak acceleration and peak velocity, respectively. Eqs.(7) and (8) give the specific peak motion on rock surface which divides the amplification characteristics of site into the linear and nonlinear response regions. Namely, the conversion factor β_a and β_v are constant for $A_r<A_r^{\ell}$ and $V_r<V_r^{\ell}$, respectively, and the factors β_a, β_v decrease with increase in peak motion on rock surface for $A_r \geqq A_r^{\ell}$ and $V_r \geqq V_r^{\ell}$, respectively.



$$S_n = 0.264\int_0^{d_s} \exp\{-0.04N(x)\} \exp(-0.14x)dx - 0.885 \quad ---(2)$$

Fig.1 Illustration for Ground Motion Intensity and Soil Parameters.

Table 1 Formulas for Determining Conversion Factors β_a and β_v.

definition of conversion factor β_a and β_v	$\beta_a = 10^{r_{0a}} \cdot A_r^{r_{1a}}$; $A_r \geqq A_r^{\ell}$ ···(3) $\beta_v = 10^{r_{0v}} \cdot V_r^{r_{1v}}$; $V_r \geqq V_r^{\ell}$ ··(4) $\beta_a = 10^{r_{0a}} \cdot (A_r^{\ell})^{r_{1a}}$; $A_r < A_r^{\ell}$ ··(5) $\beta_v = 10^{r_{0v}} \cdot (V_r^{\ell})^{r_{1v}}$; $V_r < V_r^{\ell}$ ··(6)
definition of specific value A_r^{ℓ} and V_r^{ℓ}	$A_r^{\ell} = 10^{(1.498-0.589 \cdot S_n)}$ ··(7) $V_r^{\ell} = 10^{(0.742-1.768 \cdot S_n)}$ ··(8)
coefficients appearing in Eqs. (3) - (6)	$\begin{cases} r_{0a} = 0.705 + 0.167 \cdot S_n + 0.0513 \cdot \log d_p \\ r_{1a} = -0.193 - 0.157 \cdot S_n - 0.066 \cdot \log d_p \end{cases}$ ···(9) $\begin{cases} r_{0v} = 0.454 - 0.020 \cdot S_n - 0.038 \cdot \log d_p \\ r_{1v} = -0.400 + 0.120 \cdot S_n + 0.108 \cdot \log d_p \end{cases}$ -(10)

Fig.2 shows the variation of the conversion factor for three combinations of S_n and d_p. As shown in Fig.2 the conversion factor β_a is smaller for softer ground in the case of the larger input motion; on the other hand the conversion factor β_v is larger for softer ground for the whole level of input motion. This phenomena is derived from that the nonlinearity of surface layers is dominant for higher frequency motion. The result is consistent with the significant aspects on ground motion intensities: in the case of large input motion, the peak acceleration dose not depend strongly on softness of surface layers, however the peak velocity is effected by them strongly.

Application to Spectral Ground Motion Parameters The modeling of the conversion factor for acceleration response spectra and the intensity parameter $\alpha_m(f)$ in the EMP-IB model have been performed by using the same procedure for the modeling of β_a and β_v. Herein the conversion factor $\beta_\alpha(f)$ for the intensity parameter $\alpha_m(f)$, which is related to the random vibration solution given in the next chapter, is briefly introduced.

In the EMP-IB model the rock surface ground motion is simulated from the superposition of evolutionary spectrum $G_r(t,\omega)$ which is given in the following formula.

$$\sqrt{G_r(t,\omega)}=\sqrt{G_r(t,2\pi f)}=\begin{cases}0 & ;0\leqq t<t_s \\ \alpha_m(f)\dfrac{t-t_s(f)}{t_p(f)}\exp\{1-\dfrac{t-t_s(f)}{t_p(f)}\} & ;t_s\leqq t\end{cases} \tag{11}$$

in which $t_s(f)$ and $t_p(f)$, a function of frequency f, are the starting time parameter and the duration parameter of $G_r(t,\omega)$, respectively. As shown in Fig.3 $\alpha_m(f)$ is the peak value of $\sqrt{G_r(t,\omega)}$, and is also a function of f. These parameters are scaled for magnitude and distance. For the estimation of soil surface ground motion on the basis of the EMP-IB model, the conversion factor $\beta_\alpha(f)$ for $\alpha_m(f)$ have been formulated. The intensity parameter $\alpha_{m_s}(f)$ of the evolutionary spectrum for the soil surface motion is represented by

$$\alpha_{m_s}(f)=\beta_\alpha(f)\cdot\alpha_{m_r}(f) \tag{12}$$

Table 2 gives the estimation formulas for $\beta_\alpha(f)$, and Table 3 gives the coefficients in Eq.(19). Fig.4 shows the conversion factor $\beta_\alpha(f)$ for the typical two site conditions for several earthquake intensity levels. Observe the nonlinear soil amplification effects in the different values of $\beta_\alpha(f)$ for same S_n, d_p but different M,Δ values.

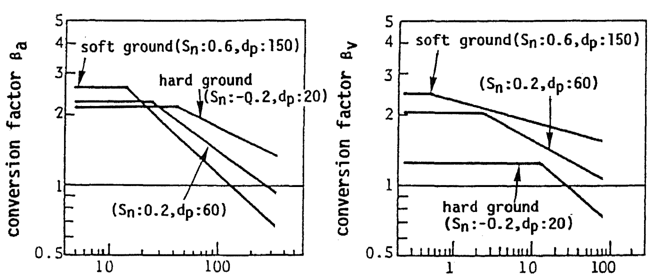


Fig.2 Example of Conversion Factor β_a and β_v for Typical Combinations of Soil Parameters.

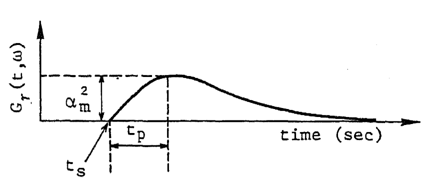


Fig.3 Time Varying Function for Modeling of Evolutionary Power Spectrum.

Table 2 Formulas for Determining Conversion Factor $\beta_\alpha(f)$.

conversion formula	$\alpha_{ms}(f)=\beta_\alpha(f)\ \alpha_{mr}(f)$	-- (13)
definition of conversion factor β_α	$f>1.0$(Hz);	
	$\beta_\alpha=10^{r_{0\alpha}}\cdot\alpha_{mr}^{\ r_{1\alpha}}$ $\quad \alpha_{mr}\geqq\alpha_{mr}^{\ell}$	-- (14)
	$\beta_\alpha=10^{r_{0\alpha}}\cdot(\alpha_{mr}^{\ell})^{r_{1\alpha}}$ $\quad \alpha_{mr}<\alpha_{mr}^{\ell}$	-- (15)
	$f\leqq1.0$(Hz);	
	$\beta_\alpha=10^{r_{0\alpha}}$	-- (16)
definition of specific value α_m^{ℓ} ($f\geqq1.0$ Hz)	$\alpha_{mr}^{\ell}=10^{(\ell_{0\alpha}+\ell_{1\alpha}Sn)}$	-- (17)
	$\begin{cases}\ell_{0\alpha}=1.135-0.643\log f+2.256(\log f)^2-2.913(\log f)^3\\ \ell_{1\alpha}=-0.350+0.286\log f-4.960(\log f)^2+4.888(\log f)^3\end{cases}$	-- (18)
coefficients appearing in Eqs. (14) - (16)	$\begin{cases}r_{0\alpha}(f)=u_{00}(f)+u_{01}(f)Sn+u_{02}(f)\log dp\\ r_{1\alpha}(f)=u_{10}(f)+u_{11}(f)Sn+u_{12}(f)\log dp\end{cases}$	-- (19)

Table 3 Values of Coefficients in Eq.(19).

f (Hz)	u_{00}	u_{01}	u_{02}	u_{10}	u_{11}	u_{12}
0.13	0.0	0.006	0.0	0.0	0.0	0.0
0.25	−0.169	0.008	0.156	0.0	0.0	0.0
0.37	−0.212	0.069	0.222	0.0	0.0	0.0
0.49	−0.192	0.098	0.236	0.0	0.0	0.0
0.61	−0.151	0.121	0.227	0.0	0.0	0.0
0.73	−0.115	0.139	0.216	0.0	0.0	0.0
0.85	−0.083	0.156	0.203	0.0	0.0	0.0
1.03	−0.035	0.178	0.184	0.0	0.0	0.0
1.45	0.032	0.256	0.160	−0.004	−0.103	−0.004
2.11	0.158	0.348	0.130	−0.015	−0.262	−0.048
3.01	0.318	0.254	0.104	−0.035	−0.266	−0.125
4.15	0.452	0.0	0.067	−0.089	−0.152	−0.176
5.53	0.507	−0.218	0.031	−0.239	−0.072	−0.144
7.03	0.540	−0.342	−0.026	−0.350	−0.040	−0.119
8.77	0.560	−0.468	−0.075	−0.441	−0.024	−0.095
10.03	0.552	−0.555	−0.100	−0.500	−0.020	−0.072

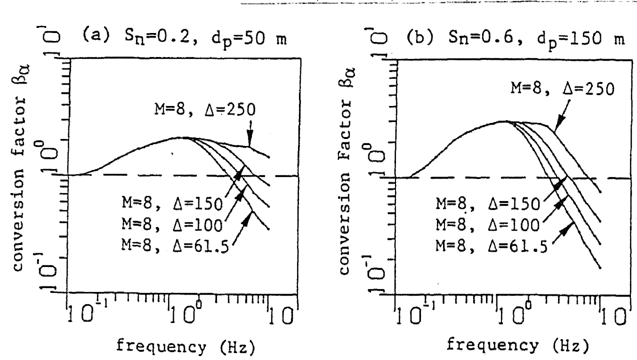


Fig.4 Example of Conversion Factor $\beta_\alpha(f)$ for Combinations of M and Δ.

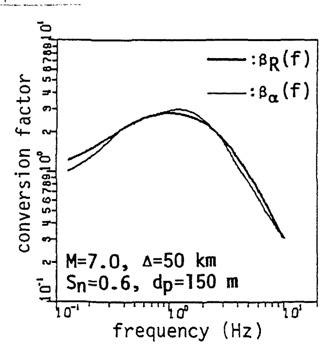


Fig.5 Example of Conversion Factor $\beta_R(f)$ compared with $\beta_\alpha(f)$.

CLOSED FORM RANDOM VIBRATION SOLUTION OF PROBABILISTIC RESPONSE SPECTRA

Stochastic Earthquake Ground Motion Model (EMP-IBRA) Kameda, Ueda, and Nojima (Ref.5) proposed the stationary earthquake motion prediction model (EMP-IBRA) on the basis of the EMP-IB model. In this stationary model the power spectrum is formulated by using the following rational function.

$$G_r(2\pi f) = \frac{2\beta_{g0}}{\pi^2 f_{P0}}\cdot\frac{\{f/f_{P0}\}^2}{[1-\{f/f_{P0}\}^2]^2+4\beta_{g0}^2\{f/f_{P0}\}^2} \tag{20}$$

Table 4 Empirical Formulas for Model Parameters in EMP-IBRA model.

$$\log \gamma = 1.950+0.5371 \cdot M-1.991 \cdot \log(\Delta+30.0) \quad ----(21)$$

$$f_{po} = 4.124+(0.0115-0.0048 \cdot M+0.000272 \cdot M^2) \cdot \Delta+(-0.7959+0.2577 \cdot M-0.01743 \cdot M^2) \cdot 10^{-4} \cdot \Delta \quad --(22)$$

$$\beta_{go} = -0.2306+0.2967 \cdot M-0.0174 \cdot M^2+(-0.0193+0.0049 \cdot M-0.0003 \cdot M^2) \cdot \Delta \quad --- (23)$$

Table 5 Formulas for Determining Conversion Factor β_R(f).

$$f_s = \left[\frac{f_1^2 f_2^2 f_3^2 \{f_1^2 \beta_1(\beta_2-\beta_3)+f_2^2 \beta_2(\beta_3-\beta_1)+f_3^2 \beta_3(\beta_1-\beta_2)}{f_1^2 f_2^2(1-\beta_3)(\beta_1-\beta_2)+f_2^2 f_3^2(1-\beta_1)(\beta_2-\beta_3)+f_3^2 f_1^2(1-\beta_2)(\beta_3-\beta_1)}\right]^{1/4} \quad ---(25)$$

$$h_s = \sqrt{\frac{\beta_1}{2(\beta_1-\beta_2)}(X_1-\frac{\beta_2}{\beta_1}X_2)} \quad --- (26) \qquad a = \sqrt{\frac{\beta_1\beta_2}{\beta_1-\beta_2}(X_1-X_2)} \quad --- (27)$$

$$X_i = 1-\frac{1}{2}(1-\beta_i)\frac{f_s^2}{f_i^2} - \frac{f_i^2}{2f_s^2} \; ; \; i=1,2 \quad ---(28)$$

where γ=peak RMS intensity and f_{p0}, β_{g0}=the characteristic parameter which determine the spectral form, and they are given in Table 4.

Conversion Factor $\beta_R(f)$ Represented by Rational Function Herein the conversion factor $\beta_R(f)$ is modeled by the following rational function of frequency f.

$$\beta_R(f) = \frac{1+2a^2(f/f_s)^2}{\{1-(f/f_s)^2\}^2+4h_s^2(f/f_s)^2} \tag{24}$$

Eq.(24) involves three parameters a, f_s, and h_s which will be determined from the site parameters and the spectral intensity of the input rock surface motion by taking account of the nonlinear soil amplification effect. These parameters are defined as in Table 5. Fig.5 shows the example for $\beta_R(f)$ compared with $\beta_a(f)$.

Random Vibration Solution of Probabilistic Response Spectra The stochastic earthquake motion model (EMP-IBRA) can be easily applied to random vibration analysis, and the spectral moments of linear structural response are obtained analytically. They can be combined with the response spectrum method developed by Der-Kiureghian (Ref.6).

In this manner, a closed form random vibration solution for the attenuation of response spectra has been obtained. The solution provides a site dependent response spectra with nonlinear soil amplification that was incorporated in the ground motion model. Thus the random vibration solution has been obtained. Its result is a lengthy formula, but can be evaluated exactly and easily, once its computer code is implemented.

Fig.6 shows a numerical result of mean response spectra for rock surface and soil surface for given values of M, Δ. Theoretical results of uncertainty of the response spectra in terms of the coefficient of variation are also shown in Fig.6. The coefficient of variation δ_U for soil surface is compared with the results derived from statistical analysis of strong motion data. Observe that the coefficient of variation δ_U for soil surface is larger than δ_U for rock surface, specially for the region around 1 Hz in which ground motion is strongly amplified by local soil conditions.

CONCLUSIONS

Following conclusions may be derived from this study.

(1) The conversion factor, β, between soil surface and rock surface motion has been developed focusing on the nonlinear amplification characteristics of soil layers over bedrocks. The conversion factor has been modeled as the function of the two simple soil parameters and corresponding earthquake motion intensity,

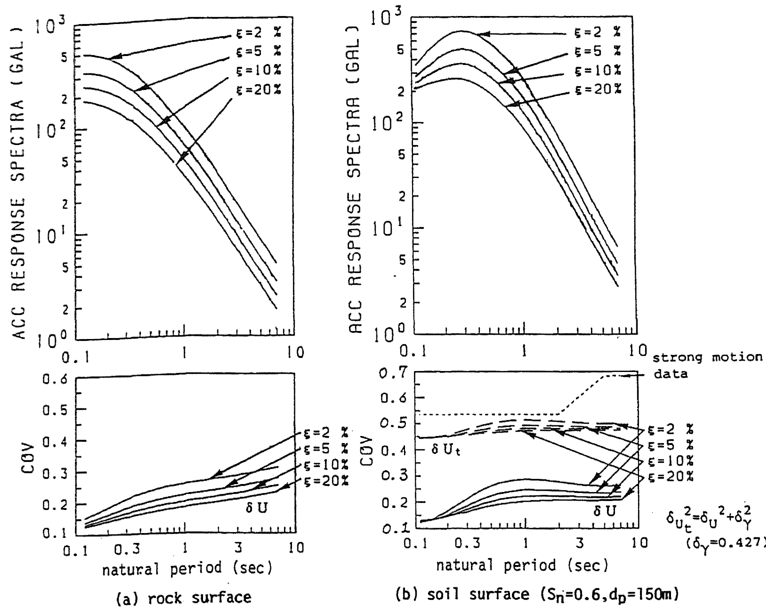


Fig.6 Mean Value and Uncertainty of Response Spectra (M=7.0, Δ=80 km).

and they have been defined for peak acceleration, peak velocity, and the intensity parameter of the evolutionary power spectrum used in the EMP-IB model.

(2) On the basis of the nonstationary earthquake motion prediction model and the proposed conversion technique, the closed form random vibration solution of probabilistic response spectra have been derived.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to Mr.J.Kimura of Kajima Construction Company for his contribution in the development of the random vibration solution of response spectra.

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