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Modeling nonlinear ground motion amplification factor by local soil parameters

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ABSTRACT: Nonlinear effect of soft surface deposit on ground motion amplification is discussed. A simple ground motion amplification model, which has been proposed on the basis of simulated earthquake motion both on rock and soil surface, is verified in the records from the recent Loma Prieta Earthquake of Oct.17, 1989. The ground motion amplification factor, called β-factor, simply relates the ground motion intensity Y_r for rock surface to Y_s for corresponding soil surface by the formula of $Y_s=\beta Y_r$. The β-factor is modeled as a function of local soil parameters such as the softness index of surface layer, depth to bedrock, and ground motion intensity Y_r which is essential for incorporating nonlinear soil amplification effect into the factor.

1 INTRODUCTION

For the seismic microzoning of ground motion intensity, the following characteristics regarding the local site condition are required to be included in the technique.

1. Simple soil parameters on local soil condition at specific sites: These parameters are obtained easily and include general soil amplification characteristic of the ground response.

2. Nonlinear effect of soil layers on the ground motion amplification: These nonlinearities are manifested primarily when the ground motions are large and consequently it is important to include them in the estimation of site ground motion forecasts. Aki and Irikura(1991) also pointed out the importance of this nonlinearity from the seismological point of view.

Considering these two fundamental features, the nonlinear soil amplification model for comprehensive earthquake microzoning has been developed (Sugito et al. 1986, 1990). The model in the previous studies was developed on the basis of the simulated earthquake motion for several levels of earthquake intensity and various types of soil conditions. The Loma Prieta Earthquake of Oct.17,1989 has brought a number of valuable records in which the nonlinear amplification characteristic of surface deposit can be observed clearly (Borcherdt, et al. 1991). This paper presents the re-evaluation of the nonlinear ground motion amplification factor for peak acceleration and peak velocity as well as acceleration response spectra on the basis of the observed records during the Loma Prieta earthquake and related information on local geology at strong motion stations in the San Francisco Bay area.

2 STRONG MOTION DATASET

The strong motion records obtained at 64 stations (Shakal, et al.,1989, and Brady, et al.,1990) was utilized to develop a data set containing pairs of strong motion records both for rock and soil surface ground conditions. The pairs of records are selected in such a way that they are geographically close to each other. Table 1 gives peak horizontal ground motion values for the pairs of strong motion stations. The local soil parameters at soil sites are also given in Table 1. In order to compare the peak ground motions between soil surface and rock surface some of these records were modified (Sugito, Kiremidjian, Shah, 1991) regarding the adjusting the components as well as the difference of site-to-fault distance in each pair data by using Joyner & Boore Formulas (1988).

Local Soil Parameters

Two simple soil parameters are used in defining the soil amplification factor. The one of them is the depth to the bedrock d_p in meters which is supposed to reflect the relatively low frequency characteristic of ground shaking at a specific site. The parameter d_p is, in general, easy to obtain for a large number of areas such as urban districts. The soil parameter d_p for the strong motion stations listed in Table 1 have been obtained from the contour maps of depth of bedrock in Bay area (Kahle, 1966 and Bonilla, 1964).

The other soil parameter used in this study is S_t which represents the softness of surface layer at specific sites. The parameter S_t is given as $S_t = v_b/v_s$ where v_s= shear wave velocity of surface layer at specific site, and v_b= standard value of shear wave velocity for very soft layer. Herein, the value v_b is fixed as v_b = 88 m/sec according to the mean value of the shear wave velocity for Bay mud deposit (Borcherdt, et al.,1979). Therefore, the parameter S_t represents the relative softness of surface layer at specific site compared with Bay mud site. The soil parameter S_t listed in Table 1 have been obtained from the investigations of shear wave velocity of soils in the Bay area (Borcherdt, 1979). In the previous study (Sugito, 1986) the soil parameter S_n which is given from the weighted integration of the blow-count profile was incorporated, however, the parameter S_t is used in this paper because of the lack of the soil profile data. The parameter S_t is substituted for S_n in the case that the blow-count profile at specific site is not available.

3 CONVERSION FACTOR FOR PEAK GROUND MOTION

Fig.1 shows the typical nonlinear soil amplification characteristic of strong ground motion. In Fig.1(a), the amplification ratio A_s/A_r (peak acceleration on soil surface A_s versus that on rock surface A_r) is plotted against the corresponding rock surface peak acceleration A_r. Fig.1(b) shows the values of V_s/V_r (peak velocity on soil surface V_s versus that on rock surface V_r) against V_r. In these figures the decrease of amplification ratio with increase in the input peak ground motion on rock surface is clearly shown, although these plots include the data for various types of soil deposits which are characterized by two soil parameters.

For the estimation of the ground motion amplification by using the soil parameters S_t and d_p, the conversion factor for peak acceleration and velocity is modeled on the basis of the data listed in Table 1. The factor, β_m can be called as conversion factor and it relates peak ground acceleration and peak velocity on rock surface and soil surface, respectively, as in the following formulas.

$$A_s = \beta_{ma} A_r, \qquad V_s = \beta_{mv} V_r \tag{1}$$

where A_s, V_s= peak acceleration and peak velocity on soil surface and A_r, V_r= those on rock surface. The subscript m of the factor β_m represents the model for the soil parameter S_t and d_p, whereas, the factor β was modeled as the function of the soil parameters S_n and d_p (1986). The conversion factor β_m is given by the formulas listed in Table 2. The constants a_0, a_1, and m characterize the nonlinear amplification effect of surface layers depending on input peak ground motion levels. These constants have been modeled as functions of local soil parameters S_t and d_p. The coefficients in the formulas have been obtained on the basis of the data listed in Table 1 by means of least square method. Fig.2 shows the values of the factors β_{ma} and β_{mv} for several combinations of local soil parameters. The general characteristic of the factors β_m and β for peak acceleration and velocity were discussed in Ref.11 (1991).

4 CONVERSION FACTOR FOR ACCELERATION RESPONSE SPECTRA

Nonlinear amplification effect in the spectral intensity is examined. Fig.3 shows the amplification of acceleration response spectra for three typical periods compared with the value of the conversion factor $\beta_s(T)$ which was modeled on the basis of simulated ground motion (1986). In Fig.3 the horizontal axis represents the values of acceleration spectra on rock surface level, and the vertical axis represents the values of the amplification ratio from rock surface to corresponding soil surface. As shown in Fig.3 the nonlinear effect is evident for shorter period range. From the results of the amplification characteristic for 20 individual periods over the range from 0.1 sec to 7.0 sec, it may be concluded that the factor $\beta_s(T)$ may be used for relatively long period range (T>2.0 sec) and relatively short range (T<0.5 sec), however, the model is to be modified in the middle period range such as 0.5 sec < T <2.0 sec.

5 CONCLUSIONS

1. A dataset of strong motion records including pairs of record for soil and rock sites has been arranged from the strong motion records in the Loma Prieta Earthquake of Oct.17, 1989. The simple two soil parameters have been defined for the use of seismic microzoning. These local soil parameters have been obtained at the stations included in the data set.

2. The nonlinear strong motion amplification factor, which converts the peak ground motion from rock surface level to soil surface level, has been defined. The factor β_{ma} for peak acceleration and β_{mv} for peak velocity, respectively, have been modeled as the functions of the two soil parameters S_t and d_p, and the peak ground motion on rock surface level on the basis of the dataset arranged in this study.

3. The nonlinear amplification effect on the spectral intensity has been examined in the Loma Prieta records. They have been compared with the former conversion factor $\beta_s(T)$ which has been modeled on the basis of simulated earthquake motion.

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Table 1 Rock Surface and Soil Surface Strong Motion Records Dataset

Soil Site Name	Soil Type	St	dp (m)	Amax1 (90°)	Amax2 (0°)	Vmax1 (90°)	Vmax2 (0°)	Rock Site Name	Rock Type	Amax1 (90°)	Amax2 (0°)	Vmax1 (90°)	Vmax2 (0°)
CDMG													
1. Treasure Island	Qhbm	1.00	86.7	-155.8	97.9	33.4	-15.6	Yerba Buena Ind	Sandstone	-65.8	28.1	14.7	4.6
2. Oakland-2-story Bldg*	Qps	0.33	85.3	-256.4	-149.8	28.2	-21.6	Piedmont*	Weathered-	97.5	49.7	13.3	4.4
3. Oakland Outer Harber*	Qhbm	1.00	97.5	-325.5	-253.6	50.7	-31.8	Piedmont*	Serpentinite	97.5	49.7	13.3	4.4
4. Gilroy #2	Qhac	0.54	140.2	316.3	-344.2	-39.2	33.3	(Gilroy #1	Sandstone	391.4	385.1	-29.5	27.9)
5. Gilroy Gavilan co.*	Qpa	0.47	25.9	363.9	-312.6	-25.5	25.5	(Gilroy #1	Sandstone	422.5	415.7	-32.6	30.8)
6. Agnew	Qhaf	0.47	231.6	157.6	163.1	-18.2	30.9	(Upper C.-Pulgas	Sandstone	-165.6	-300.0	-27.1	35.0)
7. Foster City	Qhbm	1.10	201.2	277.6	252.6	45.4	-31.8	Upper C.-Pulgas	Sandstone	-84.8	-153.6	-13.6	17.6
8. San Franci Int Airport	Qhbm	1.00	164.6	-352.8	-230.8	29.3	26.5	So-Sierra Point*	Rock	77.1	-78.9	7.0	-6.7
9. San Francisco 18story*	Qhaf	0.47	58.8	137.4	163.7	-15.6	-16.9	San Fracisco-Rincoln Hill	Sandstone	88.5	-78.6	11.8	7.3
USGS													
10. Sunnyvale South St	Qhaf	0.47	181.7	208.0	211.8	34.1	-33.4	(Upper C.-Pulgas	Sandstone	-182.3	-294.0	-26.5	34.3)
11. Hollister City Hall	Qha	0.44	55.8	251.9	216.8	-38.6	-44.0	(Gilroy #1	Sandstone	179.4	176.5	-12.2	11.5)
12. Stanford Univ Parking	Qa	0.47	36.6	-216.0	-255.0	-21.3	-33.2	Woodside	Conglomerte	79.7	79.5	-14.7	15.6
13. APEEL Array. Redwood*	Qhbm	1.00	91.4	238.6	-244.2	49.6	36.4	Upper C.-Pulgas	Sandstone	-84.8	-153.8	-13.8	17.6
14. San Fran 600 Montgo St	Qhafs	0.47	43.6	119.4	-107.1	18.1	-9.6	San Francisco-Telegraph Hill	Sandstone	80.5	-51.2	9.6	6.5

* : Peak ground motions have been obtained from time histories processed by the transformation of coordinates systems.
(: Peak ground motion have been modified accoding to Joyner & Boore's attenuation formulas.

Table 2 Estimation Formulas for Conversion Factors β_{ma} and β_{mv}.

peak acceleration

$$\log \beta_{ma} = (a_0 - a_1 \log A_r)^m - 1.5$$

$$\begin{cases} a_0 = 5.37-3.92S_t+1.67 \log d_p \\ m = 0.35+0.25S_t+0.021 \log d_p \\ a_1 = 3.35-2.21S_t+0.65 \log d_p \end{cases}$$

peak velocity

$$\log \beta_{mv} = (a_0 - a_1 \log V_r)^m - 1.5$$

$$\begin{cases} a_0 = 8.91 - 2.62S_t+0.10 \log d_p \\ m = 0.22+0.153S_t+0.054 \log d_p \\ a_1 = 3.35-2.21S_t+0.65 \log d_p \end{cases}$$

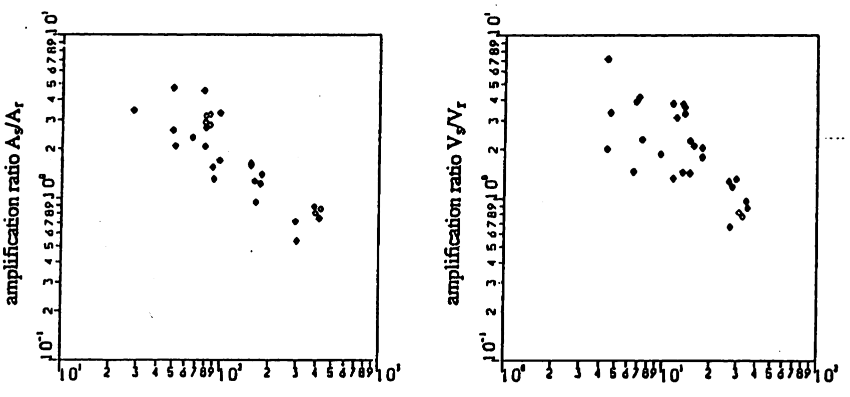

Fig.1 Variation of Ground Motion Amplification Ratio versus Rock Surface Ground Motion.

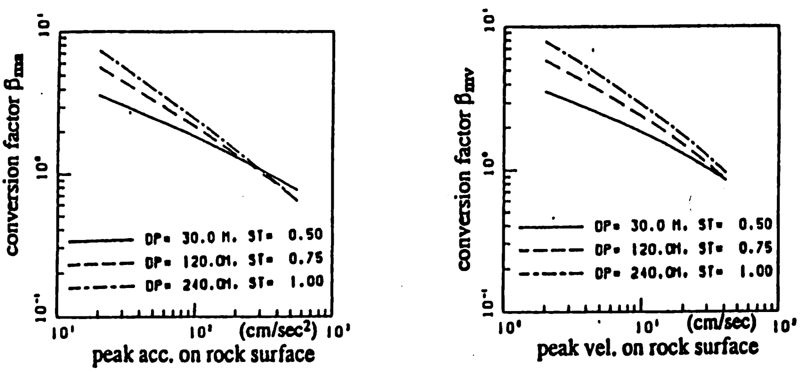

Fig.2 Variation of Conversion Factor β_{ma} and β_{mv} for Combination of Local Soil Parameter.

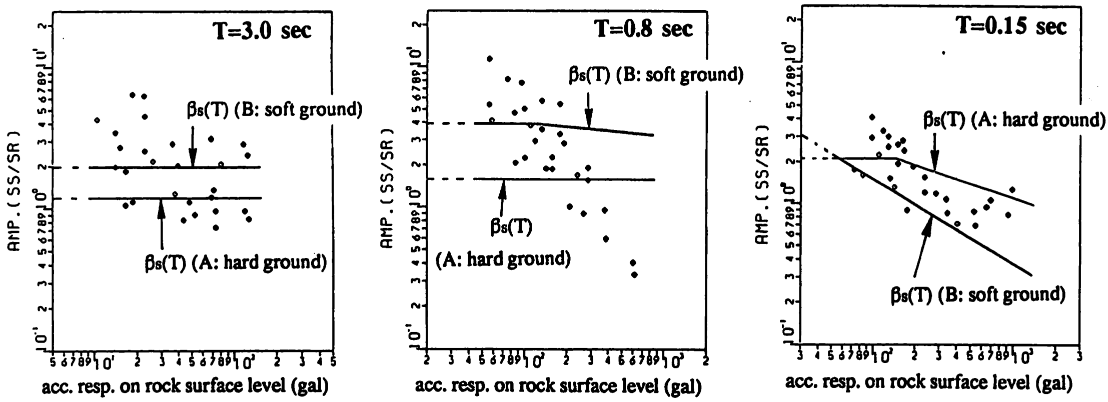

Fig.3 Amplification Characteristic of Acceleration Response Spectra Compared with Values of the Conversion Factor $\beta_s(T)$. The values of $\beta_s(T)$ is obtained for the typical two soil conditions: A (hard ground, S_n=-0.085, d_p=25.9 m) and B (soft ground, S_n=0.92, d_p= 231.6 m). The Soil Parameter S_n is estimated from the relation as $S_n = 1.5\ S_t - 0.58$ (Sugito, Kiremidjian, Shah, 1991).

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