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ATTENUATION OF PEAK GROUND MOTIONS AND ABSOLUTE ACCELERATION RESPONSE SPECTRA OF VERTICAL EARTHQUAKE GROUND MOTION

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Multiple regression analyses for vertical peak ground motions (peak ground acceleration, peak ground velocity and peak ground displacement) and absolute acceleration response spectra with damping ratio of 5 % of critical are presented. Employed were 119 sets of vertical strong motion acceleration records obtained at 53 free field sites in Japan. Empirical formulae of these characteristics in terms of earthquake magnitude and epicentral distance are proposed for three subsoil conditions. Peak ground motions and absolute acceleration response spectra of vertical components were compared with those of horizontal components, and characteristics of vertical components were discussed in comparison with the characteristics of horizontal components.

1. INTRODUCTION

For determining appropriate seismic effects to be considered in design of structures, it is essential to assess intensities and frequency characteristics of severe ground motions. One of the characteristics of earthquake ground motions of considerable interest in design is the peak values of ground motions, i. e., peak ground accelerations, velocity and displacement. Earthquake response spectra, as defined by the maximum response of a single degree of freedom system, may be more relevant parameters to represent the characteristics of ground shaking because they account for both frequency characteristics and intensities of ground motion.

Because of its interests to engineers, many studies have been conducted on attenuation characteristics of peak ground motions and earthquake response spectra for horizontal ground motions in the past decade[1]. However, relatively few studies have been made of for attenuation of vertical ground motions. This was due in all probably to insignificant number of vertical strong motion records available.

In this paper, multiple regression analyses were made for vertical peak ground motions (peak ground acceleration, velocity and displacement) and vertical absolute acceleration response spectra with 5 % damping ratio. Attenuations of these characteristics in terms of earthquake magnitude and epicentral distance are proposed for three subsoil conditions with use of Japanese strong motion data.

2. STROMG MOTION DATA ANALYZED

A total of 119 sets of vertical strong motion acceleration recorde were used in the analysis. They were

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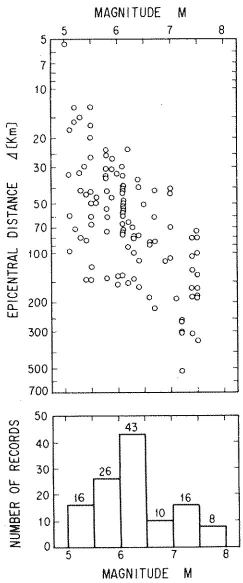
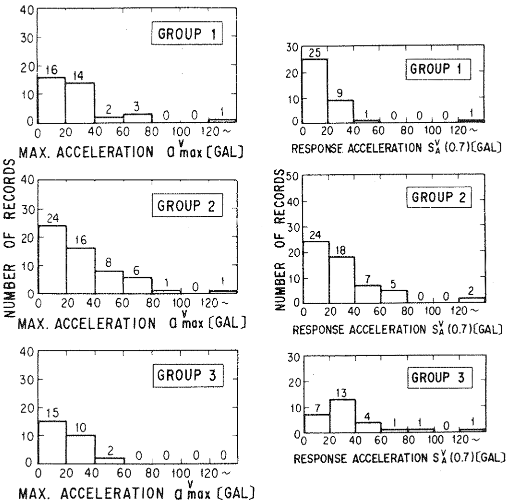


Fig. 1 Classification of Records in terms of Earthquake Magnitude and Epicentral Distance.



(a) Peak Acceleration (b) Response Acceleration

Fig. 2 Distribution of Peak Acceleration and Response Acceleration (T=0.7 s).

recorded between May 1965 and June 1980 at 53 free field sites in Japan[2),3)], and any records on structures including the first floor and basement were excluded. Only records with earthquake magnitude greater than or equal to 5.0 and with focal depth less than 60 km were considered. Fig. 1 shows the classification of the records in terms of earthquake magnitude and epicentral distance. It is apparent from Fig. 1 that near-field records induced by large magnitude earthquakes are quite few. Only seven earthquakes with magnitude of 7.0 or greter, which include the Niigata Earthquake of 1964, the Tokachi-oki Earthquake of 1968 and the Miyagiken-oki Earthquake of 1978, were analyzed. It is also seen from Fig. 1 that approximately three quarters of the total records were derived from earthquake with magnitude less than 7.0. Fig. 2 shows the distribution of peak ground accelerations and absolute acceleration response spectra with 5 % damping ratio of critical (natural period of 0.7 second).

Ground conditions at recording sites were classified into three groups in accordance with Table 1. This classification essentially depends on Japanese practice adopted in the Earthquake Resistant Design Specifications of Highway Bridges (ERDSHB)[4)]. A slight modification was, however, incorporated into the ERDSHB classification, i.e., the original classification of ERDSHB has four categories for subsoil conditions, whereas three conditions were considered in this analysis by putting groups 2 and 3 of ERDSHB clasification into the same group. This modification was made because the difference between group 2 and group 3 of the ERDSHB classification is small in the ground motions represented in terms of peak ground motions and earthquake response spectra.

Table 1 Classification of Ground Conditions.

Soil Condition in this Analysis	Classification of Highway Bridge Specifications		Definition by Natural Period
	Soil Condition	Geological Definition	
Group-1	Group-1	Tertiary or older rock, or diluvium with H < 10m	$T_G < 0.2$sec
Group-2	Group-2	Diluvium with H ≧ 10m, or alluvium with H < 10m	$0.2 < T_G < 0.4$sec
	Group-3	Alluvium with H < 25m including soft layer with thickness less than 5m	$0.4 < T_G < 0.6$sec
Group-3	Group-4	Other than the above, usually soft alluvium or reclaimed land	$T_G > 0.6$sec

All the data analyzed were provided by SMAC accelerograph. Because sensitivity at high frequency is substantiarily low in SMAC accelerograph, instrumental correction was performed considering accuracy of digitization of strong motion records[5)]. Ground velocity and displacement were calculated by integrating the corrected acceleration in frequency domain. The cut-off frequency of 1/3 Hz and 12 Hz was assigned in instrumental correction and integration of acceleration.

3. ATTENUATION OF PEAK GROUND MOTIONS

In analyzing the attenuation of peak ground motions by means of multiple regression analysis, attenuation equations have to be properly selected. According to the previous study on the attenuation of peak values of horizontal ground motions, following two attenuation equations give good approximation[6].

$$X^V(M, \Delta, GC_i)=a(GC_i)\times 10^{b(GC_i)M}\times(\Delta+30)^{c(GC_i)} \quad (1)$$

$$X^V(M, \Delta, GC_i)=a(GC_i)\times 10^{b(GC_i)M}\times(\Delta+30)^{c} \quad (2)$$

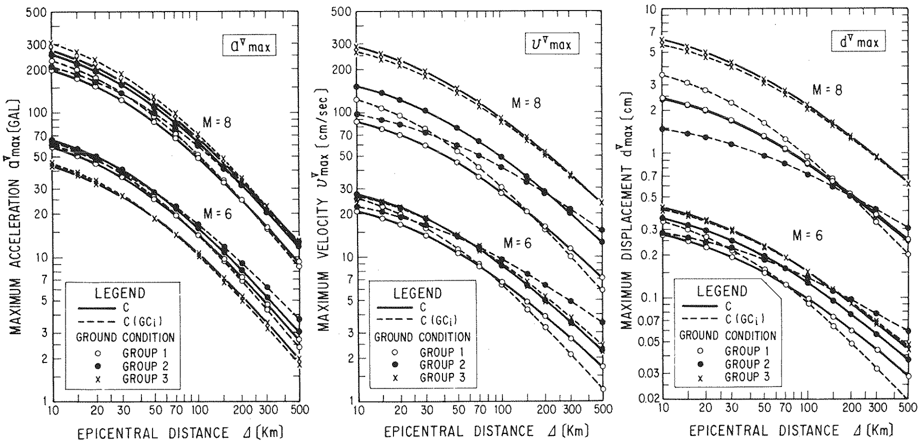
in which $X^V(M, \Delta, GC_i)$ represents peak ground motions under consideration, i.e., peak acceleration a^V_{max} (gal), peak velocity v^V_{max} (cm/s) and peak displacement d^V_{max} (cm), for a given magnitude of earthquake M, epicentral distance Δ (km) and subsoil condition GC_i (i=1, 2, 3). Coefficients $a(GC_i)$, $b(GC_i)$ and $c(GC_i)$ are the constants to be determined for each subsoil condition, whereas coefficient c is the constant determined by assuming that c is independent of subsoil conditions. The only difference between Eq. (1) and Eq. (2) is the dependence of coefficient c, which represents attenuation rate of peak ground motion with epicentral distance, on subsoil conditions. Although it is often claimed that the epicentral distance is not necessarily a suitable parameter to represent the distance from source of energy released by eathquake, this was used here because the epicentral distance is the only parameter which can be definitely determined for all earthquakes analyzed in this study.

Multiple regression analysis was performed with use of the attenuation equations of Eqs. (1) and (2) based on 119 sets of vertical peak ground motions. As a result, coefficients of Eqs. (1) and (2) were determined as shown in Table 2. The results show that difference of coefficient in accordance with subsoil condition in Eq. (1) is insignificant for a^V_{max}, which gives credit to assume that coefficient c is independent of subsoil condition as defined by Eq. (2). In comparison, coefficient c in Eq. (1) changes significantly depending on subsoil condition in case of v^V_{max} and d^V_{max}. Therefore, for v^V_{max} and d^V_{max} there is not definite physical justification to assume that coefficient c is independent of subsoil condition. The comparisons of predicted attenuation between Eq. (1) and Eq. (2) will be described later. It shold be noted here that coefficients a and b tend to change with respect to a^V_{max}, v^V_{max} and d^V_{max}in a similar manner between Eq. (1) and Eq. (2). Of particular interest in Table 2 is coefficient b, which represents the effect of earthquake magnitude on the peak ground motions. Depending on subsoil conditions coefficient b takes a value of 0.2 to 0.4 in magnitude for a^V_{max} while it is approximately 0.3 to 0.5 and 0.4 to 0.6 in magnitude for v^V_{max} and d^V_{max}, respectively. It implies that a unit increase of earthquake magnitude produces more pronounced increase of peak value in v^V_{max} and d^V_{max} than in a^V_{max}.

Fig. 3 shows comparisons of attenuation of a^V_{max}, v^V_{max} and d^V_{max} predicated by Eq. (1) and Eq. (2) for earthquake magnitued of 6 and 8. The results show that the predicted attenuations of a^V_{max} between Eq. (1) and Eq. (2) are so small that they are regarded as practically the same. Therefore Eq. (2) is proposed here to represent attenuation of a^V_{max}. On the other hand, although overall attenuation characteristics of v^V_{max} and d^V_{max} are similar between Eq. (1) and Eq. (2), there is a certain difference, i.e., in case of peak displacement, d^V_{max} predicted by Eq. (1) for a combination of M=8 and Δ=30 km is 2.3 cm, 1.1 cm and 4 cm for subsoil conditions of group 1, 2 and 3, respectively, while d^V_{max} predicted by Eq. (2) for the same condition is 1.7 cm, 1.7 cm and 4.2 cm. Although difference is less significant than d^V_{max} similar differences are seen for attenuation of v^V_{max}. As was described above, because effect of subsoil conditions on coefficient c is pronounced, justification

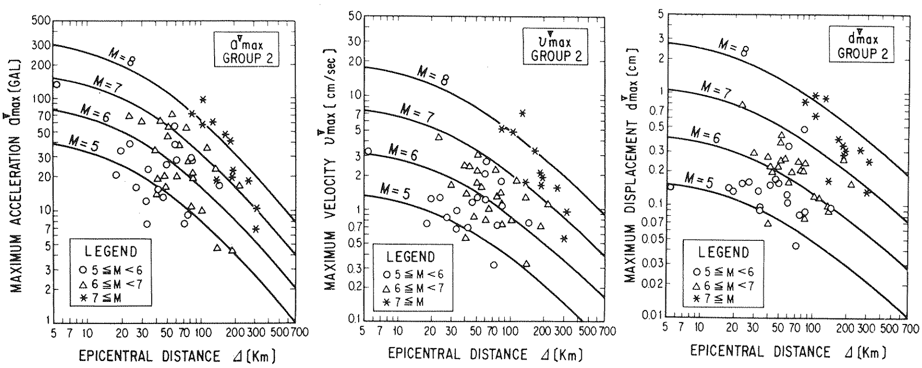
Table 2 Coefficients a, b and c, and Correlation Coefficient R

Ground Motion	Ground Group	Eq. (1)				Eq. (2)			
		a	b	c	R	a	b	c	R
a^V_{max}	1	145.8	0.281	−1.277	0.770	117.0	0.268		
	2	73.22	0.273	−1.078	0.551	88. 19	0.297	−1.190	0.984
	3	23.2613	0.419	−1.240	0.575	13.49	0.402		
v^V_{max}	1	1.766	0.343	−1.183	0.821	1.024	0.311		
	2	0.370	0.323	−0.720	0.588	0.374	0.374	−0.968	0.748
	3	0.870	0.499	−0.931	0.632	0.511	0.511		
d^V_{max}	1	0.0182	0.509	−1.112	0.856	0.474	0.474		
	2	0.185	0.361	−0.611	0.680	0.417	0.417	−0.879	0.964
	3	0.00367	0.569	−0.849	0.654	0.00363	0.579		



(a) Peak Acceleration a^V_{max} (b) Peak velocity v^V_{max} (c) Peak Displacement d^V_{max}

Fig. 3 Comparison of Predicted Attenuation Between Eq. (1) and Eq. (2).



(a) Peak Acceleration a^V_{max} (b) Peak velocity v^V_{max} (c) Peak Displacement d^V_{max}

Fig. 4 Comparison of Peak Ground Motions Between Observed and Predicted by Eq. (2).

to assume Eq. (2) for v^V_{max} and d^V_{max} is not deduced directly from Table 2. Nevertheless, as is apparent from the above-described comparisons of d^V_{max} predicted for $M=8$ and $\Delta=30$ km, the overall variation of d^V_{max} in accordance with subsoil condition is considered more realistic in Eq. (2) than Eq. (1). Therefore it was decided here to propose Eq. (2) even for v^V_{max} and d^V_{max} as a first trial. Further investigation is, of course, needed for attenuation characteristics of v^V_{max} and d^V_{max} on the basis of accumulating more strong motion data.

Fig. 4 shows a comparision of predicted peak acceleration, velocity and displacement with the observed ones. Only the results for group 2 are presented because the other results exhibit the same inclinations. It is understood from Fig. 4 that although overall variations of the observed values in terms of M and Δ are predicted by Eq. (2), deviation from the predicted values is significant. The reason for such a large scatter is considered to be caused by insufficiency of the parameters assumed in the attenuation equation, i.e., although three principal parameters are selected for factors that may influence the peak ground motions, there are many other factors such as properties of path condition, focal mechanism, deeper site condition, etc. It is therefore necessary to consider the scatter of the predicted value around the observed one when the above attenuations are to be used for practical purpose. For this purpose, ratios of the observed and predicted peak ground motions are defined as

$$U_a = a^{VOB}_{max} / a^{VP}_{max}, \quad U_v = v^{VOB}_{max} / v^{VP}_{max}, \quad U_d = d^{VOB}_{max} / d^{VP}_{max} \cdots\cdots (3)$$

in which superscript OB and P denote the observed and predicted values, respectively. The standard deviation of log U_a, log U_v and log U_d are 0.253, 0.223 and 0.224, respectively.

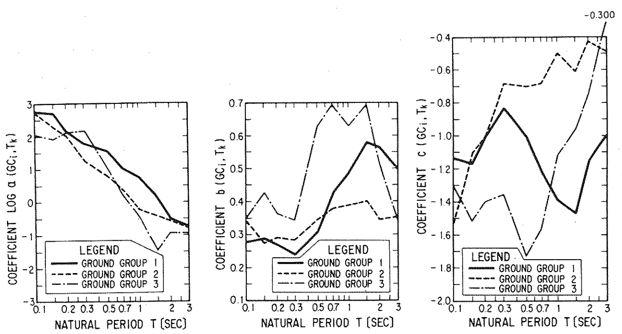
4. ATTENUATION OF ABSOLUTE ACCELERATION RESPONSE SPECTRA

Absolute acceleration response spectral amplitude S_A^V with damping ratio of 5% of critical corresponding to natural period T_k (k=1, 2, ……, 10) and subsoil condition GC_i (i=1, 2, 3) was assumed to be represented in terms of earthquake magnitude M and epicentral distance Δ (km) as

$$S_A^V(T_k, M, \Delta, GC_i)=a(T_k, GC_i)\times 10^{b(T_k,GC_i)M}\times(\Delta+30)^{c(T_k,GC_i)} \quad (4)$$

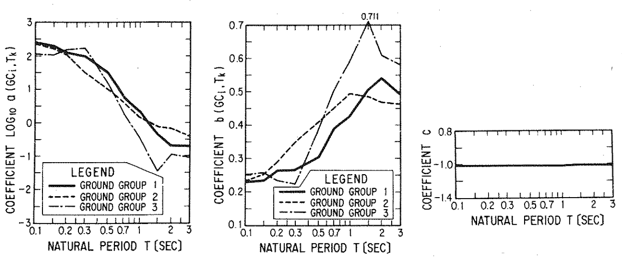
$$S_A^V(T_k, M, \Delta, GC_i)=a(T_k, GC_i)\times 10^{b(T_k,GC_i)M}\times(\Delta+30)^{c} \quad (5)$$

in which coefficients $a(T_k, GC_i)$, $b(T_k, GC_i)$ and $c(T_k, GC_i)$ are the constants to be determined by multiple regression analysis for each nautral period T_k (k=1, 2, ……, 10) and subsoil condition GC_i (i= 1, 2, 3). On the other hand coefficient c is a constant which is determined by assumming that c is independent of both natural period and subsoil condition. As was the case for peak ground motions, Eqs. (4) and (5) were adopted because they give good approximation for attenuation of horizontal acceleration response spectra[6),7)]. The only difference between Eq. (4) and Eq. (5) is the dependence of coefficient c on natural period and subsoil condition. The natural period T_k was assumed as 0.1, 0.15, 0.2, 0.3, 0.5, 0.7, 1, 1.5, 2 and 3 second so that intervals of natural periods analyzed become almost equal in logarithmic scale.



(a) Coefficient $a(GC_i, T_k)$ (b) Coefficient $b(GC_i, T_k)$ (c) Coefficient $c(GC_i, T_k)$

Fig. 5 Coefficients $a(GC_i, T_k)$, $b(GC_i, T_k)$ and $c(GC_i, T_k)$ of Eq. (4).



(a) Coefficient $a(GC_i, T_k)$ (b) Coefficient $b(GC_i, T_k)$ (c) Coefficient c

Fig. 6 Coefficients $a(GC_i, T_k)$, $b(GC_i, T_k)$ and c of Eq. (5).

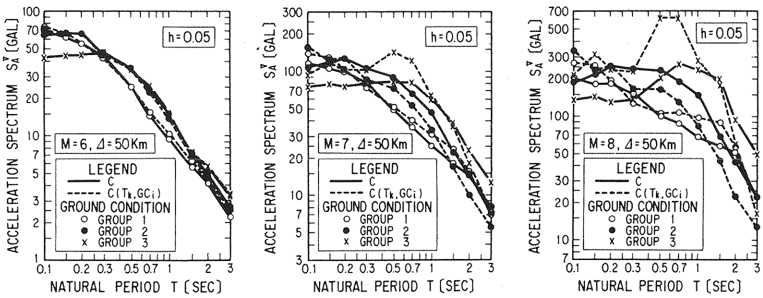
Figs. 5 and 6 show the variation of the coefficients with respect to natural period T for three subsoil conditions (coefficients of Eq. (5) are shown in Table 3). Although variation of the coefficients a and b with respect to T is large because of insufficient number of the strong motion records analyzed, it is obvious that coefficient a decreases with increasing natural period, and that coefficient b has reverse inclination with coefficient a. It should be noted that such characteristics are the same between Eqs. (4) and (5).

It is noteworthy here that coefficient b, which represents effects of earthquake magnitude on absolute acceleration spectral amplitude for a fixed combination of epicentral distance and subsoil condition, increases with increasing natural period. The magnitude of b is about 0.25 to 0.4 for

Table 3 Coefficients $a(T_k, GC_i)$, $b(T_k, GC_i)$ and c of Eq. (5).

Natural Period T_k[sec]	Ground Group 1		Ground Group 2		Ground Group 3	
	a(Tk,GCi)	b(Tk,GCi)	a(Tk,GCi)	b(Tk,GCi)	a(Tk,GCi)	b(Tk,GCi)
0.1	246.4	0.230	224.8	0.232	114.5	0.251
0.15	207.2	0.235	168.4	0.255	107.8	0.258
0.2	124.1	0.263	105.5	0.288	155.7	0.232
0.3	95.72	0.267	31.92	0.351	171.1	0.228
0.5	31.86	0.304	10.44	0.410	13.82	0.388
0.7	5.869	0.388	4.039	0.451	1.939	0.509
1.0	2.185	0.428	1.386	0.495	0.352	0.596
1.5	0.441	0.506	0.758	0.486	0.0343	0.711
2.0	0.203	0.541	0.670	0.468	0.105	0.619
3.0	0.196	0.497	0.389	0.462	0.0886	0.584

c= −1.015



(a) $M=6$ (b) $M=7$ (c) $M=8$

Fig. 7 Comparison of Spectral Amplitude Predicted by Eq. (4) and Eq. (5).

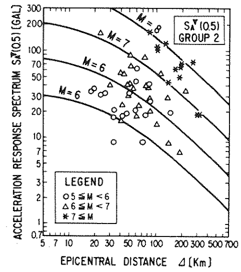


Fig. 8 Comparison of Spectral Amplitude Between Observed and Predicted by Eq. (5) (Natural Period $T=0.5$ s, Ground Group 2).

Table 4 Standard Deviation of log U_{SA}.

Sound Group	T=0.1s.	T=0.15s.	T=0.2s.	T=0.3s.	T=0.5s.	T=0.7s.	T=1s.	T=1.5s.	T=2s.	T=3s.
1	0.341	0.265	0.202	0.207	0.249	0.259	0.247	0.258	0.236	0.200
2	0.323	0.329	0.289	0.275	0.257	0.252	0.277	0.242	0.260	0.243
3	0.249	0.229	0.199	0.161	0.189	0.235	0.258	0.243	0.224	0.239

natural periods shorter than about 0.3 s, implying than a unit increase in earthquake magnitude develops approximately a 2-fold increase in the response acceleration. On the other hand, the magnitude of b is approximately 0.4 to 0.7 for natural period longer than about 0.7 s, i. e., a unit increase in earthquake magnitude develops approximately a 3 to 5-fold increase in the response spectral amplitude. This clearly show that ground motion at long periods are characterized by earthquakes large in magnitude, which is a trend repeatedly discussed for horizontal ground motion by previous investigators[1),6)].

Coefficient c in Eq. (4) takes a value from -0.3 to -1.7 depending on natural period and subsoil condition. Although this difference is substantial it should be noted that variation of coefficient c with respect to period and subsoil condition is not consistent. In comparison, coefficient c in Eq. (5) takes a value of about-1.0.

Fig. 7 shows comparisons of spectral ampiltudes predicated by Eqs. (4) and (5) for three combinations of earthquake magnitude and epicentral distance. The results show that differences of spectral values predicted by both equations are less significant with the exception of spectral amplitudes in group 3 for natural period between 0.5 and 1 s. At this natural period range, consecutive value of spectral amplitude predicted by Eq. (4) exhibits abrupt changes while such sudden changes are not developed in spectral amplitude predicted by Eq. (5). Therefore as was the case of peak ground motions, although appreciable dependence of coefficient c on natural period and subsoil conditions does not necessarily give credit to assume Eq. (5), Eq. (5) was judged appropriate to represent attenuation of spectral amplitude.

Fig. 8shows comparisons between observed values and those predicted by Eq. (5) for natural period of 0.5 second and ground group 2. It is seen that the predicted attenuation of spectral amplitude represents the general trend of the observed spectral amplitude.

As is the case of peak ground motions, ratio of observed spectral amplitued S_A^{VOB} and the predicted amplitude S_A^{VP} is defined as

$$U_{SA}=S_A^{VOB}/S_A^{VP} \quad \cdots\cdots (6)$$

The standard deviations of log U_{SA} are shown in Table 4. It should be noted that they are almost independent of earthquake magnitued and epicentral distance.

5. COMPARISONS WITH ATTENUATION OF HORIZONTAL GROUND MOTIONS

According to a previous study on attenuation charateristics of horizontal ground motions[6),7)], attenuation of horizontal peak ground motions $\tilde{X}^H$ (peak ground acceleration $\tilde{a}^H_{\max}$ (gal), velocity $\tilde{v}^H_{\max}$ (cm/s) and displacement $\tilde{d}^H_{\max}$ (cm)) and horizontal absolute acceleration response spectral amplitude $\tilde{S}^H_A$ (gal) with

Table 5 Coefficient $a^H(GC_i)$, $b^H(GC_i)$ and c^H of Eq. (7).

Type	Ground Group	$a^H(GCi)$	$b^H(GCi)$	c^H
$\tilde{a}^H_{max}$	1	987.4	0.216	
	2	232.5	0.313	-1.218
	3	403.8	0.265	
$\tilde{v}^H_{max}$	1	20.8	0.263	
	2	2.81	0.430	-1.222
	3	5.11	0.404	
$\tilde{d}^H_{max}$	1	0.626	0.372	
	2	0.062	0.567	-1.254
	3	0.070	0.584	

Table 6 Coefficient $a^H(T_k, GC_i)$ and $b^H(T_k, GC_i)$ of Eq. (8).

Natural Period T(sec)	Ground Group 1		Ground Group 2		Ground Group 3	
	$a^H(T_k,GC_i)$	$b^H(T_k,GC_i)$	$a^H(T_k,GC_i)$	$b^H(T_k,GC_i)$	$a^H(T_k,GC_i)$	$b^H(T_k,GC_i)$
0.1	2420	0.211	848.0	0.262	1307	0.208
0.15	2407	0.216	629.1	0.288	948.2	0.238
0.1	1269	0.247	466.0	0.315	1128	0.228
0.3	574.8	0.273	266.8	0.345	1263	0.224
0.5	211.8	0.299	102.2	0.388	580.6	0.281
0.7	102.5	0.317	34.34	0.440	65.67	0.421
1.0	40.10	0.344	5.04	0.548	7.41	0.541
1.5	7.12	0.432	0.719	0.630	0.803	0.646
2.0	5.78	0.417	0.347	0.644	0.351	0.666
3.0	1.67	0.462	0.361	0.586	0.262	0.635

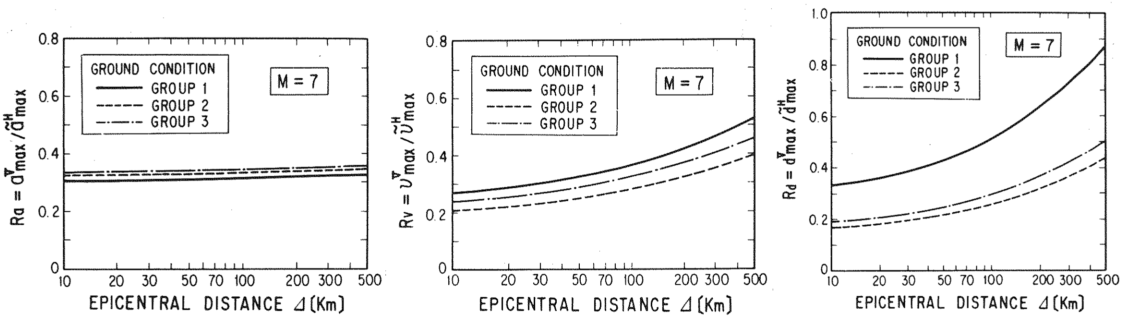


Fig. 9 Ratios R_a, R_v and R_d for $M=7$.

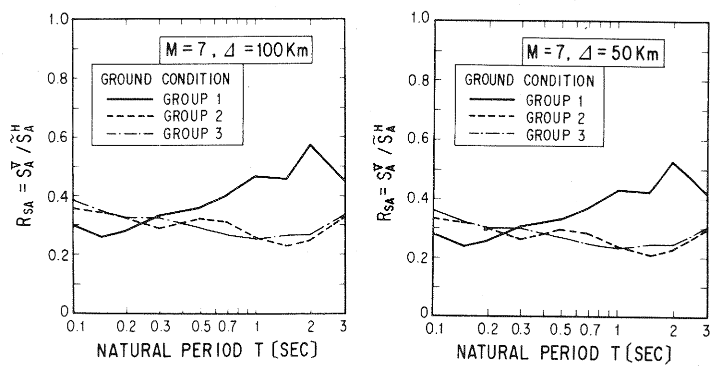


Fig. 10 Ratio R_{SA} for Earthquake Magnitude of 7.0 and Epicenral Distance of 50 and 100 km.

5 % damping ratio are given as

$$\tilde{X}^H(M, \Delta, GC_i)=a^H(GC_i)\times 10^{b^H(GC_i)M}\times(\Delta+30)^{c^H} \cdots\cdots (7)$$

$$\tilde{S}^H_A(T_k, M, \Delta, GC_i)=a^H(T_k, GC_i)\times 10^{b^H(T_k,GC_i)M}\times(\Delta+30)^{-1.178} \cdots\cdots (8)$$

in which coefficients $a^H(GC_i)$, $b^H(GC_i)$ and c^H of Eq. (7) and coefficients $a^H(T_k, GC_i)$ and $b^H(T_k, GC_i)$ are given in Table 5 and Table 6, respectively.

It should be noted here that analytical procedure and attenuation equation in developing Eqs. (7) and (8) are all the same with this study. It should be also noted that 119 sets of vertical ground motion data used in this study were obtained by the same sites and earthquakes with 197 sets of two orthogonal horizontal ground motions, which were used in developing Eqs. (7) and (8). Due to smaller amplitude of acceleration in vertical motions than in horizontal motions, some vertical records were missed during recording and digitizing processes. Ratios of peak ground motions and absolute acceleration response spectra between vertical and horizontal components are then defined as

$$R_a=a^V_{max}/\tilde{a}^H_{max},\quad R_V=v^V_{max}/\tilde{v}^H_{max},\quad R_d=d^V_{max}/\tilde{d}^H_{max} \cdots\cdots (9)$$

$$R_{SA}=S^V_A/\tilde{S}^H_A \cdots\cdots (10)$$

Substituting Eqs. (2), (5), (7) and (8) into Eqs. (9) and (10), one can estimate the ratios for a specific combination of earthquake magnitued M, epicentral distance Δ and subsoil condition. Figs. 9 and 10 show such an example of R_a, R_v, R_d and R_{SA} for earthquake magnitude of 7. It is seen that ratio R_a and R_{SA} takes approximately 1/3 with a few exception. Ratio R_v and R_d increase with increasing epicentral distance. However it is considered necessary to re-evaluate R_v and R_d from the accuracy point of view of attenuation equation of v^V_{max} and d^V_{max}.

6. CONCLUSIONS

The preceding pages present the results of multiple regression analysis of vertical peak ground motion and absolute acceleration response spectra with 5 % damping ratio. Attenuations of peak ground motions (peak ground acceleration a^V_{max}, velocity v^V_{max} and displacement d^V_{max}) and absolute acceleration response amplitude S^V_A were proposed by Eqs. (2) and (5), respectively, in terms of earthquake magnitude, epicentral distance and subsoil conditions. Scatter of the observed value from the predicted amplitude as defined by Eqs. (3) and (6) was approximately 0.22 to 0.25. According to comparisons with previous study on horizontal ground motions, peak ground accelerations and absolute acceleration response spectral amplitued of vertical componte are approximately 1/3 of those values for horizontal component, and the ratio is almost independent of earthquake magnitude and epicentral distance.

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