

Attenuation Relations of Peak Ground Acceleration and Acceleration Response Spectra for Engineering Applications

Keiichi TAMURA*

Shunsuke MATSUMOTO**

and

Yoshihiro NAKAO**

Synopsis

We develop a consistent set of simple and practical attenuation relations for peak ground acceleration and 5% damped response spectral acceleration in terms of earthquake magnitude and distance. The strong ground motion data analyzed in the present study consist of 432 horizontal components of acceleration records from 40 earthquakes in Japan. We employ a two-step stratified regression procedure in order to decouple the determination of magnitude coefficient from the determination of distance coefficient, and demonstrate the validity of this technique by comparing the result with that obtained by general non-stratified regression analysis. We also propose a method to modify the developed attenuation relations by soil condition.

Key Words: *Attenuation relation, peak ground acceleration, acceleration response spectra, regression analysis, seismic design*

要旨

本論文では、1995 年兵庫県南部地震を含む 40 地震による 432 成分の水平成分強震記録をもとに、二段階回帰分析を用いて最大加速度及び加速度応答スペクトルの距離減衰式を導出した。解析では、機械式（SMAC 型）強震計記録については計器補正を行うとともに、水平 2 成分の合成を施し、水平面内での最大加速度または最大加速度応答スペクトル振幅を解析対象とした。また、通常の重回帰分析による距離減衰式をあわせて算出し、強震記録に含まれるマグニチュードと距離の相関性を分離して回帰係数を決定する二段階回帰分析の優位性を示した。さらに、導出された距離減衰式に対して地盤条件の補正方法を提示した。

キーワード： 距離減衰式、最大加速度、加速度応答スペクトル、回帰分析、耐震設計

Received on January 14, 2003

* Dr. of Eng., Team Leader, Ground Vibration Research Team, Public Works Research Institute
1-6 Minamihara, Tsukuba-shi, Ibaraki-ken 305-8516 Japan

** Research Engineer, Earthquake Disaster Prevention Division, National Institute for Land and Infrastructure Management
1 Asahi, Tsukuba-shi, Ibaraki-ken 305-0804 Japan

1. Introduction

The predictive estimation of strong ground motion is one of primary interests in earthquake engineering. For this purpose, both theoretical and semi-empirical methods to simulate ground motion time series have been vigorously studied, however, the effectiveness of attenuation relation of ground motion is never less distinct, and it is widely used for engineering applications. Attenuation relations are efficacious, for example, in determining design ground motions, and they are particularly helpful in probabilistic seismic hazard analysis, in which a wide range of earthquake sizes and locations are incorporated. Among various quantitative measures that represent ground motion characteristics, such as peak acceleration, peak velocity, response spectra and spectrum intensity, peak ground acceleration has been most widely chosen for analysis, because it is the most simple representative of accelerogram or acceleration time series, and has long been used for the basis of calculating inertia force in the seismic design of structures. The most useful measure for current engineering practice, however, may be response spectrum, because it represents the maximum seismic response taking account of the natural period and damping of structure. The acceleration response spectrum is widely used as a basis of seismic load in designing structures. For instance, it underlies the relationship between lateral design force and period of structure in the static design procedure of various engineered structures. It also prescribes design response spectrum for the dynamic analysis of structures including the Trans-Tokyo Bay Highway¹⁾ and Akashi Kaikyo Bridge²⁾.

Attenuation relations are usually derived from regression analysis of strong motion data, and diverse relations have been proposed to predict peak ground acceleration^{3) ~ 6)}, with the accumulation of strong motion data and development of new regression analysis technique. A number of attenuation relationships have also been developed for acceleration response spectra^{7) ~ 9)}, and the comprehensive reviews of attenuation relations in the early stages may be found in the previous publications^{10) ~ 13)}.

Since strong ground motion is recorded as the ground shaking exceeds certain trigger level of accelerograph, far-source ground motion records are generally obtained only from large events. On the other hand, near-source records are mostly from small to moderate earthquakes, though the number of large events has gradually been increasing. These facts result in a positive correlation between earthquake magnitudes and distances of strong motion data, which may exert inappropriate influence upon the distance coefficient of attenuation relation obtained by regression analysis^{3) ~ 6)}. In order to avoid this influence, Joyner and Boore³⁾ adopted a two-step stratified regression procedure to produce an attenuation relation of peak

ground acceleration in 1981, which was further applied by a number of investigators^{6), 9), 14) ~ 16)}.

Persistent efforts have been continuously expended on studying attenuation relationships of ground motion, which may be reviewed in the recent works^{15), 17) ~ 22)}. Major interests of the recent studies include the functional form of attenuation relation, regional variability of earthquakes and effect of site condition. Regarding the functional form of attenuation relation, various predictive equations have been developed by examining the source and seismic wave propagation characteristics. The concept of equivalent hypocentral distance was proposed to integrate a finite-size fault with an attenuation relation, for which a point-source model is commonly assumed²³⁾. General independent variables chosen for attenuation relationships are earthquake size, source-to-site distance and geological site condition. In addition to these, attenuation relations have been developed for the specific seismo-tectonic regions^{24) ~ 26)}, i.e., active tectonic regions, subduction zones and stable continental regions. Also derived are the attenuation relations for crustal, inter-plate and intra-plate earthquakes based on Japanese strong motion data²⁷⁾, and several studies have focused on the style of faulting^{15), 24)}. Instead of the conventional geological site classification, there have been attempts to use the average shear-wave velocity as a continuous measure to represent site effects on ground motions^{15), 28)}.

As described in the former section, the recent studies of attenuation relationships have mainly laid emphasis on constructing more physically meaningful predictive equations. On the other hand, the developed attenuation relations generally have complicated functional forms with a number of parameters, and furthermore some of them have rather restricted applicability, resulting in a fact that they may not be necessarily incorporated into engineering practice. Reflecting over those facts, the primary objective of present study is to develop a consistent set of practical attenuation relations for predicting peak ground acceleration and acceleration response spectra, which is readily applicable to engineering applications. We intend in this study to derive a simple empirical attenuation formula having a few parameters, instead of pursuing physical strictness. Near-source ground motion records obtained from the 1995 Hyogo-ken Nanbu earthquake in Japan are included in the analysis to complement the conventional strong motion database. Instrumental correction is performed for the records obtained by mechanical type accelerographs, because their sensitivity over high frequency range is essentially suppressed. Each two horizontal components of acceleration record are combined to yield the maximum peak acceleration on the horizontal plane, and we use this as the acceleration measure for regression analysis. Similarly, we calculate the maximum response spectral acceleration on the horizontal plane. We employ a two-step stratified regression procedure in this study,

and derive simple and reasonable attenuation relations for both peak ground acceleration and acceleration response spectra. We also introduce a ratio of recorded ground motion to the predicted value by the developed attenuation relation, and propose a method to modify the attenuation relation by soil condition of recording site.

2. Strong Motion Data

We use 216 pairs of two horizontal components of strong motion accelerations in numerical analysis. We in principle restrict the strong motion records for analysis to those obtained by the former Public Works Research Institute in order to secure consistency in accelerograph installation and data processing. They were recorded at 109 free field sites in Japan from 40 earthquakes. The earthquakes analyzed are from the 1967 Kinkazan-oki earthquake through the 1995 Hyogo-ken Nanbu (Kobe) earthquake. We selected these earthquakes based on the following criteria: 1) earthquake magnitude ≥ 5.0 , 2) focal depth ≤ 60 km, and 3) three or more records were obtained in each earthquake. The Japan Meteorological Agency (JMA) magnitude M_J is employed as a magnitude scale, because this magnitude is most commonly used in Japan and homogeneously determined for earthquakes occurred in and around Japan. Earthquakes with large magnitudes include the 1993 Hokkaido Nansei-oki earthquake ($M_J=7.8$), 1983 Nihonkai-chubu earthquake ($M_J=7.7$), 1968 Hyuganada earthquake ($M_J=7.5$) and so forth. The reason why we restrict the earthquakes with three or more strong motion records is that we examine attenuation rates of ground motions for individual earthquakes prior to the two-step stratified regression analysis presented later in this paper.

We employ the shortest distance between the recording station and the fault plane as the distance measure in attenuation relation, when the earthquake source parameters are available. This distance has an advantage of being physically reasonable definition of distance. In cases where source parameters are not available, epicentral distance is used as the distance measure. The shortest and epicentral distances are assigned for 102 and 114 strong motion data, respectively. They were recorded from 15 and 25 earthquakes, respectively. **Fig.1** shows the distribution of analyzed data in magnitude and distance. As might be expected, a positive correlation is observed between these two quantities.

We use strong motion records obtained by both digital and mechanical type (SMAC) accelerographs. Since the sensitivity of SMAC accelerograph deteriorates at high frequency and certain error is included during digitization process, we introduce instrumental correction for frequencies between 1/3 Hz and 12 Hz based on the reliable recording range of SMAC accelerograph^{29), 30)}.

The resultant of two horizontal components of acceleration

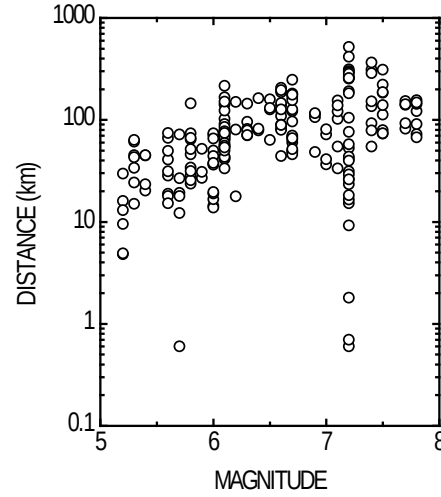


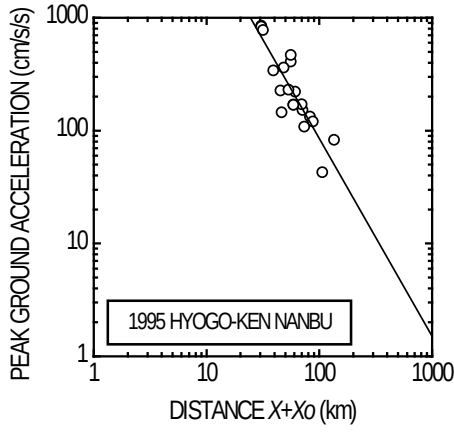
Fig.1 Distribution of analyzed data in magnitude and distance

Table 1 Soil condition classification

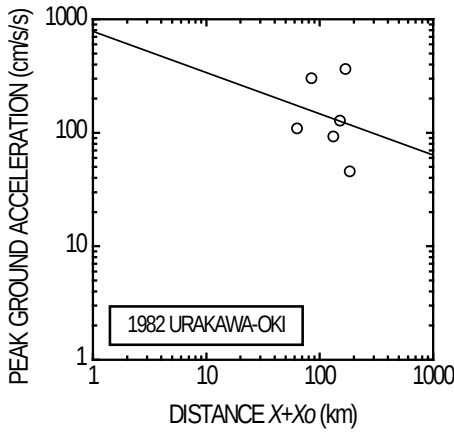
Soil condition	Natural period (s)	Geological description
Group-1	$T_G < 0.2$	Rock or shallow soil deposits
Group-2	$0.2 \leq T_G < 0.6$	Diluvium or alluvium
Group-3	$0.6 \leq T_G$	Soft alluvium

record is computed at each time step, and the maximum value over the record duration is defined as the peak horizontal acceleration. This is because the two horizontal components of ground motion record provided by an accelerograph merely correspond to ground shaking in the direction that the accelerograph is installed, and do not necessarily represent the maximum value on the horizontal plane. In the case of acceleration response spectrum, we first calculate acceleration response time series of the single-degree-of-freedom system, which has a specified natural period, from the two horizontal components of each acceleration record, respectively. The damping ratio h is assumed to be 5% in this calculation. Then we compute a vectorial combination of two acceleration response time series at each time step, and define the maximum value over the duration as acceleration response spectral measure for analysis.

Since ground motion characteristics and resultant structural damage are closely related to the surface geology or local soil condition, we classify soil conditions of recording sites into three groups according to the fundamental natural period of ground as described in **Table 1**. This classification depends on the design specifications for highway bridges in Japan³¹⁾, and **Table 2** gives the number of recording sites and data for each soil condition group. The earthquakes and strong motion records analyzed with site condition classifications are listed in the Appendix of this paper.



(a) 1995 Hyogo-ken Nanbu earthquake ($R=0.88$)



(b) 1982 Urakawa-oki earthquake ($R=0.20$)

Fig.2 Attenuation of peak ground acceleration for individual earthquakes

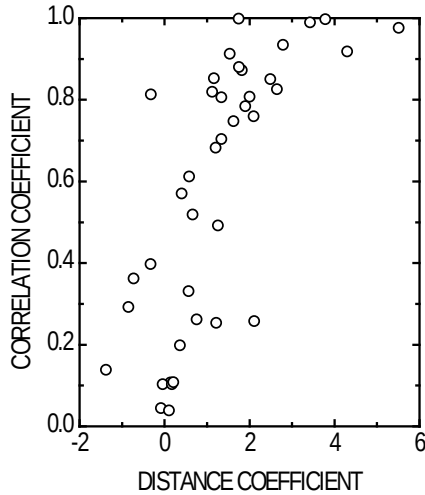


Fig.3 Relationship between distance coefficient and correlation coefficient for peak ground motion

3. Regression Model and Results

3.1 Regression model

The following empirical formula is assumed to represent the

Table 2 Number of recording sites and records

Soil condition	Number of sites	Number of records
Group-1	26	53
Group-2	54	100
Group-3	29	63

attenuation of peak ground acceleration and response spectral acceleration:

$$\log Y = \log a + b \cdot M - c \log(X + X_0) \quad (1)$$

where Y is either peak ground acceleration or 5% damped response spectral acceleration at a specified natural period T (cm/s^2), M is JMA magnitude, X is distance (km), X_0 is a constant accounting for ground motion saturation at short distance, and a , b and c are regression coefficients to be determined. X_0 is herein assumed to be 30km after Kawashima *et al.*^{5), 11)}. In the first stage of two-step stratified regression analysis, we assume that the coefficient c in eq. (1) is uniquely assigned for all earthquakes and $\log a + b \cdot M$ is replaced by $\sum \delta_i \alpha_i$ for an individual earthquake as

$$\log Y = \sum_i \delta_i \cdot \alpha_i - c \log(X + X_0) \quad (2)$$

in which δ_i is a dummy variable ($=1$ for the i -th earthquake, $=0$ otherwise) and α_i is a coefficient for the i -th earthquake. In the second stage, we determine the coefficients a and b by regression analysis using α_i and magnitude of each earthquake. Note that in the present technique each strong motion record has the same weight in determining the distance coefficient c and each earthquake has the same weight in determining the magnitude coefficient b .

Prior to the two-step stratified regression analysis, we examined the attenuation characteristics of peak ground acceleration and response spectral acceleration for each earthquake, because ground motion records in individual earthquakes do not always exhibit physically meaningful attenuation. For this purpose, we assumed eq. (1) with the specified magnitude for each earthquake, and computed the distance coefficient and correlation coefficient by least squares fit, as shown in **Fig.2** for the case of peak ground acceleration. **Fig.3** presents the relationship between distance coefficient and correlation coefficient. Similar analysis was conducted with response spectral acceleration at each natural period. Based on those results, we selected the earthquakes and ground motion records that proceed to the two-step stratified regression analysis by using the following criteria: 1) distance coefficient $c > 0$, and 2) correlation coefficient $R \geq 0.25$. The criterion for correlation coefficient is based on a somewhat arbitrary choice. Consequently, 169 pairs of horizontal peak accelerations obtained from 28 earthquakes were selected for the regression

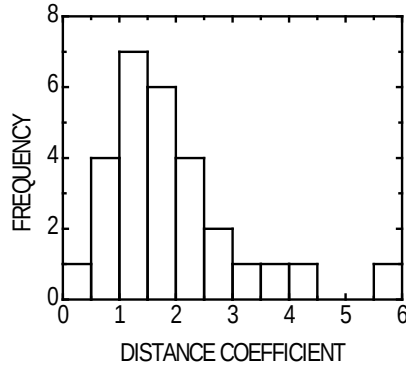


Fig.4 Frequency distribution of distance coefficients of peak ground acceleration for individual earthquakes

analysis. **Fig.4** shows the frequency distribution of distance coefficients for those 28 earthquakes, where the median is calculated as 1.685. Regarding the response spectral acceleration, **Table 3** summarizes the number of strong motion records and corresponding earthquakes that are chosen for the regression analysis, and the median of distance coefficients derived from individual earthquakes.

3.2 Results of regression analysis

In addition to the two-step stratified regression analysis, general non-stratified regression analysis was also conducted for comparison, and the regression coefficients of eq. (1) by both analyses are given in **Table 4** for peak ground acceleration. The distance coefficient c by two-step stratified analysis is larger than that of non-stratified regression analysis, and the former is well consistent with the median of attenuation rates for individual earthquakes obtained in the preliminary analysis. Concerning the magnitude coefficient b , the two-step stratified regression analysis yields larger value than the non-stratified regression analysis, similar to the case of coefficient c . These facts imply that both earthquake magnitude and distance are more influential in the result of two-step stratified analysis than that of non-stratified analysis.

The coefficients of attenuation relation for response spectral acceleration at each natural period are shown in **Table 5**. **Fig.5** illustrates the variation of regression coefficients with respect to natural period, where the median of attenuation rates computed for individual earthquakes is also indicated. Both the coefficients b and c obtained by two-step stratified regression analysis are larger than those by non-stratified analysis, and the coefficient c by two-step stratified analysis is harmonious with the attenuation rate obtained from individual earthquakes. These traits coincide well with the result for attenuation relation of peak ground acceleration. The magnitude coefficient b in **Fig.5** becomes large as natural period becomes long, in general. On the other hand, the distance coefficient c does not exhibit such systematic variation with natural period.

Table 3 Number of records and earthquakes selected for regression analysis on response spectral acceleration, and median of distance coefficients

Natural period (s)	Number of records	Number of earthquakes	Median of distance coefficients
0.1	179	31	1.966
0.15	181	32	1.707
0.2	170	28	1.782
0.3	168	27	1.794
0.5	139	20	1.513
0.7	147	24	1.468
1	135	23	1.948
1.5	132	23	1.852
2	140	24	1.812
3	124	20	1.484

Table 4 Coefficients of attenuation relation for peak ground acceleration

Coefficient	a	b	c
Two-step stratified regression	416.0	0.390	1.610
Non-stratified regression	206.1	0.300	1.175

Table 5 Coefficients of attenuation relation for 5% damped response spectral acceleration

(a) Two-step stratified regression analysis

Natural period (s)	a	b	c
0.1	2151	0.371	1.752
0.15	1030	0.407	1.689
0.2	822.9	0.419	1.667
0.3	299.2	0.458	1.613
0.5	89.94	0.493	1.499
0.7	62.24	0.537	1.612
1	19.71	0.684	1.900
1.5	2.960	0.769	1.933
2	1.147	0.771	1.849
3	0.4782	0.712	1.619

(b) Non-stratified regression analysis

Natural period (s)	a	b	c
0.1	1174	0.261	1.269
0.15	584.2	0.291	1.192
0.2	446.7	0.297	1.146
0.3	157.8	0.354	1.143
0.5	48.61	0.419	1.131
0.7	36.11	0.446	1.212
1	10.28	0.521	1.252
1.5	2.043	0.589	1.280
2	0.6800	0.623	1.262
3	0.3879	0.621	1.287

Fig.6 shows the resultant attenuation curves of peak ground acceleration, which were derived by two-step stratified and non-stratified regression analyses, for $M=5, 6, 7$ and 8 . Also plotted are the analyzed data. We see from this figure that the attenuation relation by two-step stratified regression analysis is more magnitude dependent and more distance dependent than that by general non-stratified analysis. The newly proposed attenuation formula based on the two-step stratified regression procedure agrees well with the attenuation characteristics of

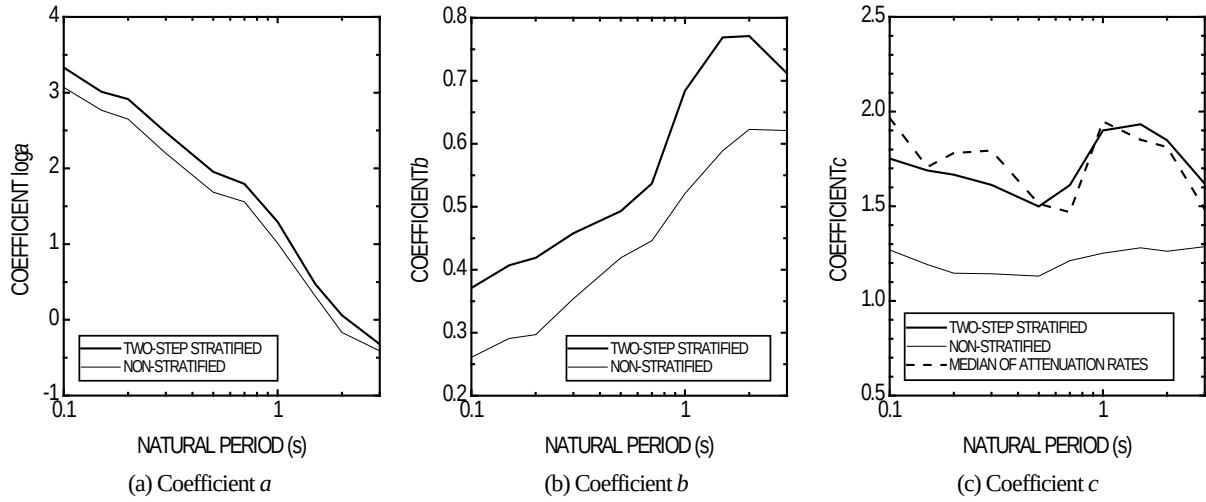


Fig.5 Variation of regression coefficients of attenuation relation for response spectral acceleration

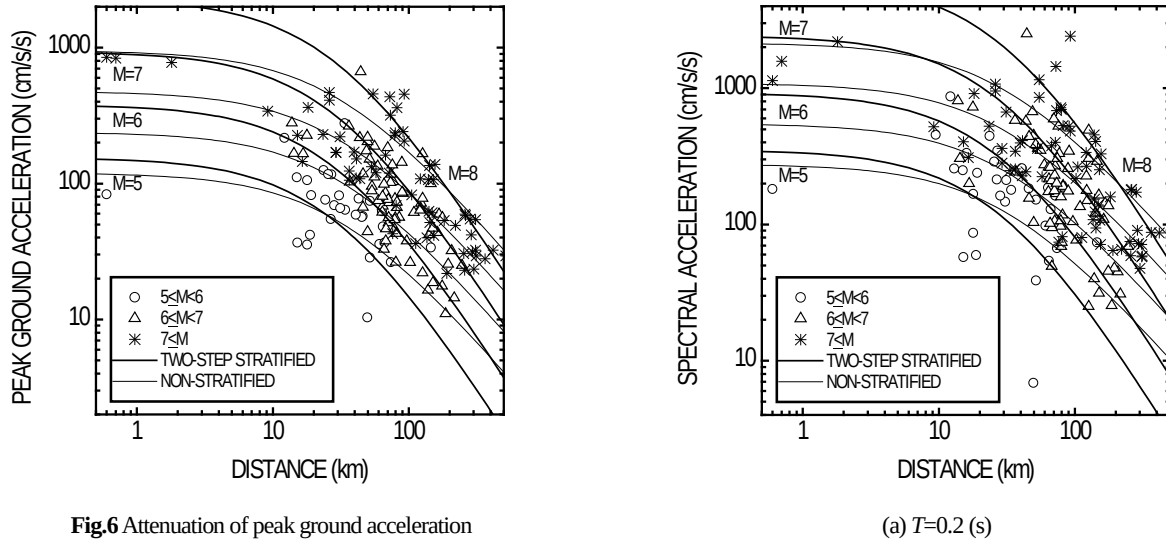


Fig.6 Attenuation of peak ground acceleration

recorded peak ground accelerations, though certain scatter of measured data is observed around the predicted value.

The attenuation curves of response spectral acceleration, together with those calculated from the strong motion data, are plotted in **Fig.7**. Results are shown for spectral accelerations at $T=0.2$ and 2 (s), which are chosen as representatives of short and long natural periods, respectively. Attenuation rates are similar between these two natural periods. The difference of spectral value associated with that of magnitude is larger in the case of $T=2$ (s). This is because the coefficient of magnitude term is large for long natural period. Comparing the results of two-step stratified and non-stratified regression analyses, the attenuation relation by the former is more magnitude dependent and more distance dependent than that by the latter, as expected earlier.

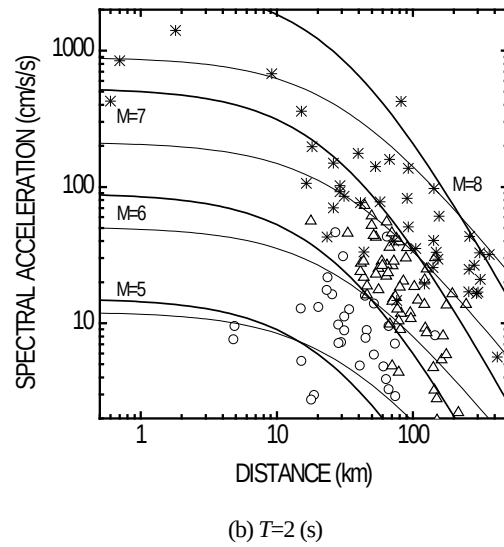


Fig.7 Attenuation of 5% damped response spectral acceleration

3.3 Modification of attenuation relation by soil condition

As previously mentioned, a two-step stratified regression

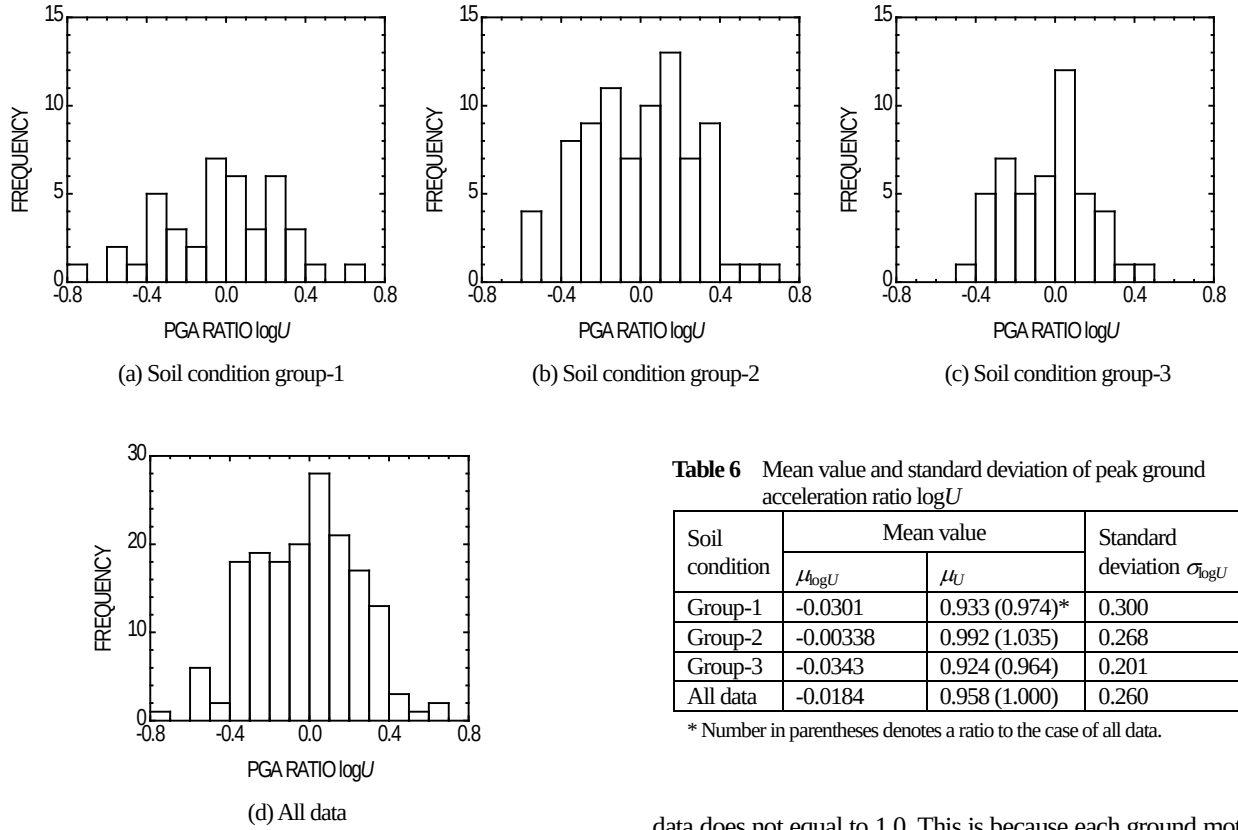


Fig.8 Frequency distribution of peak ground acceleration ratio $\log U$

procedure has an advantage of decoupling the interrelationship between magnitude and distance in the analyzed data, whereas this technique requires the sufficient number of both ground motion records and earthquakes that provided them, in order to yield satisfactory result. Due to this constraint, further accumulation of strong motion records is necessary to apply the technique to each sub-dataset of ground motion records classified by soil condition. Hence, to investigate effects of soil condition on peak ground acceleration or response spectral acceleration, we introduce a ratio of recorded ground motion to the predicted one. This ratio is defined as

$$U = Y_R / Y_P \quad (3)$$

where Y_R is either recorded peak ground acceleration or response spectral acceleration calculated from strong motion record, and Y_P is the predicted value by eq. (1) with the specified magnitude and distance.

Fig.8 shows the frequency distribution of $\log U$ for each soil condition group and all the data in the case of peak ground acceleration. The distribution of $\log U$ may be approximated by a normal distribution. **Table 6** lists the mean value and standard deviation of $\log U$ for each soil condition group, where the mean value of U is also indicated. They are expressed as $\mu_{\log U}$, $\sigma_{\log U}$ and μ_U in this table, respectively. Note that μ_U for all the

Table 6 Mean value and standard deviation of peak ground acceleration ratio $\log U$

Soil condition	Mean value		Standard deviation $\sigma_{\log U}$
	$\mu_{\log U}$	μ_U	
Group-1	-0.0301	0.933 (0.974)*	0.300
Group-2	-0.00338	0.992 (1.035)	0.268
Group-3	-0.0343	0.924 (0.964)	0.201
All data	-0.0184	0.958 (1.000)	0.260

* Number in parentheses denotes a ratio to the case of all data.

data does not equal to 1.0. This is because each ground motion record does not have the same weight for determining the magnitude coefficient of attenuation relation in the two-step stratified regression procedure, though it has the same weight in the determination of distance coefficient. Therefore we use the ratio of μ_U for each soil condition group to that for all the data, which is denoted with parentheses in **Table 6**, in order to study the dependency of peak ground acceleration on soil condition. On an average, peak ground acceleration at the soil condition group-2 site is 4 % larger, and those at groups-1 and 3 sites are 3 to 4 % smaller than the prediction by eq. (1) without soil condition classification. This signifies that the influence of soil condition upon peak ground acceleration is insignificant within the scope of present study.

Similarly, $\mu_{\log U}$, $\sigma_{\log U}$ and μ_U are calculated for response spectral accelerations as given in **Table 7**, and **Fig.9** plots the variation of μ_U with respect to natural period. As indicated in this figure, the average response spectral acceleration ratio for soil condition group-1 decreases from 1.2 to 0.5 over the natural period range $0.1 \leq T \leq 1$ (s) and then increases for $1 \leq T \leq 3$ (s), while the average spectral acceleration ratio for group-3 increases from 0.8 to 1.4 for $0.1 \leq T \leq 1$ (s) and then decreases for $1 \leq T \leq 3$ (s). Comparing to the cases of soil condition groups-1 and 3, the variation of average response spectral acceleration ratio for group-2 with natural period is less significant. These ratios may be applicable to modify the developed attenuation relation by soil condition.

Table 7 Mean value and standard deviation of response spectral acceleration ratio $\log U$

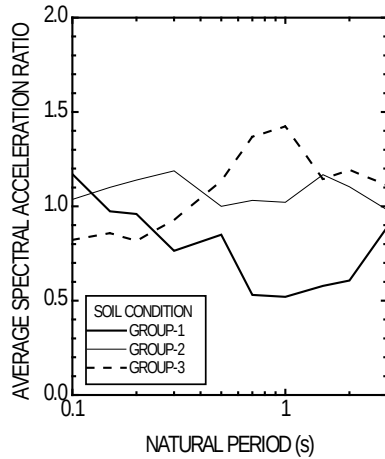
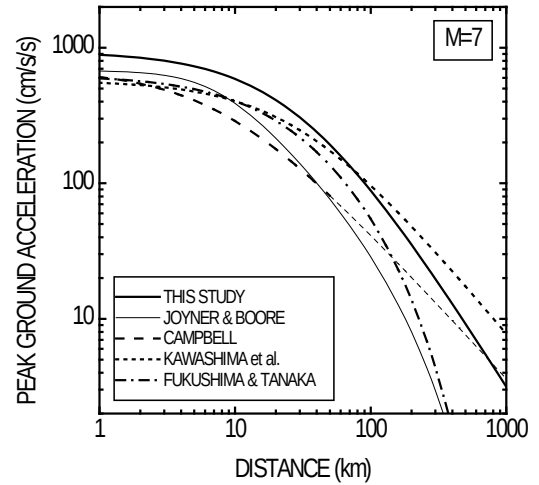
Natural period (s)	Soil condition group-1			Soil condition group-2			Soil condition group-3			All data		
	Mean value		$\sigma_{\log U}$	Mean value		$\sigma_{\log U}$	Mean value		$\sigma_{\log U}$	Mean value		$\sigma_{\log U}$
	$\mu_{\log U}$	μ_U		$\mu_{\log U}$	μ_U		$\mu_{\log U}$	μ_U		$\mu_{\log U}$	μ_U	
0.1	0.0474	1.115(1.171)*	0.297	-0.00549	0.987(1.037)	0.309	-0.1064	0.783(0.822)	0.257	-0.0213	0.952	0.298
0.15	-0.0331	0.927(0.973)	0.311	0.0206	1.049(1.101)	0.281	-0.0880	0.817(0.858)	0.309	-0.0212	0.952	0.300
0.2	-0.0357	0.921(0.959)	0.387	0.0390	1.094(1.139)	0.327	-0.1054	0.784(0.817)	0.256	-0.0177	0.960	0.332
0.3	-0.1278	0.745(0.764)	0.361	0.0639	1.158(1.188)	0.319	-0.0439	0.904(0.927)	0.260	-0.0111	0.975	0.326
0.5	-0.0835	0.825(0.850)	0.244	-0.0126	0.971(1.000)	0.289	0.0422	1.102(1.135)	0.246	-0.0128	0.971	0.272
0.7	-0.2958	0.506(0.531)	0.406	-0.00701	0.984(1.032)	0.283	0.1157	1.305(1.368)	0.265	-0.0205	0.954	0.334
1	-0.3216	0.477(0.521)	0.435	-0.0287	0.936(1.022)	0.354	0.1155	1.305(1.424)	0.347	-0.0381	0.916	0.397
1.5	-0.2656	0.543(0.578)	0.366	0.0395	1.095(1.168)	0.361	0.0309	1.074(1.145)	0.282	-0.0277	0.938	0.362
2	-0.223	0.598(0.607)	0.389	0.0366	1.088(1.104)	0.337	0.0704	1.176(1.193)	0.274	-0.00637	0.985	0.348
3	-0.0669	0.857(0.888)	0.253	-0.0233	0.948(0.982)	0.293	0.0306	1.073(1.112)	0.222	-0.0153	0.965	0.268

* Number in parentheses denotes a ratio to the case of all data.

Table 8 Definition of attenuation model parameters for peak ground acceleration

Investigator(s)	Peak ground acceleration	Magnitude*	Distance
Joyner and Boore ³⁾	Larger of the two horizontal peak values	M_W	Closest distance to the surface projection of fault rupture
Campbell ⁴⁾	Mean of the two horizontal peak values	M_S for M_S and $M_L \geq 6.0$ M_L for M_S and $M_L < 6.0$	Closest distance to the fault rupture zone
Kawashima <i>et al.</i> ⁵⁾	Maximum of vectorial combination of two horizontal components	M_J	Epical distance
Fukushima and Tanaka ⁶⁾	Mean of the two horizontal peak values	M_S	Hypocentral distance (for Japanese data)

* M_W : Moment magnitude, M_S : Surface-wave magnitude, M_L : Local magnitude, M_J : JMA magnitude

**Fig. 9** Variation of average response spectral acceleration ratio**Fig.10** Comparison of attenuation relations for peak ground acceleration ($M=7$)

4. Comparison of Results

4.1 Peak ground acceleration

We herein compare our result with the previous studies by Joyner and Boore³⁾, Campbell⁴⁾, Kawashima *et al.*⁵⁾, and Fukushima and Tanaka⁶⁾. Definitions of peak ground acceleration, magnitude and source-to-site distance are different by investigators as summarized in **Table 8**. Since our principal objective is to compare the general trends of attenuation relationships, we do not make compensation for those differences, while it may be useful to survey them for the further detailed comparison. This motivates us to briefly

review the parameter differences that underlie various attenuation relations.

Campbell⁴⁾ found that the larger of the two horizontal peak accelerations is on the average 13 % larger than the mean of two peak values. Kawashima *et al.*³²⁾ reported that the maximum amplitude of vectorial combination of two horizontal accelerations is approximately 8 % greater than the larger of the two horizontal peaks. Utsu³³⁾ studied the relationships between various magnitude scales, and proposed the average deviations from moment magnitude. According to

Table 9 Definition of attenuation model parameters for response spectral acceleration

Investigators	Spectral acceleration measure	Magnitude*	Distance	Soil condition classification	Other parameters
Kawashima <i>et al.</i> ⁽⁸⁾	Maximum of vectorial combination of two horizontal spectral amplitudes	M_I	Epicentral distance	3 groups by the fundamental natural period of ground	–
Abrahamson and Silva ⁽²⁴⁾	Geometric mean of two horizontal spectral amplitudes	M_W	Closest distance to the fault rupture zone	- Rock or shallow soil - Deep soil	- Fault type - Hanging wall effect
Boore <i>et al.</i> ⁽¹⁵⁾	Geometric mean of two horizontal spectral amplitudes	M_W	Closest distance to the surface projection of fault rupture	Average shear wave velocity over the upper 30m	- Fault type

* M_I : JMA magnitude, M_W : Moment magnitude

his result, differences between surface-wave magnitude, JMA magnitude and moment magnitude are inconspicuous around magnitude $M=7$, for which we compare attenuation relations in the following section of this paper. Among various distance measures between source and recording site, general measures used for attenuation relations may be divided into the following two categories: 1) closest distance to the fault rupture zone and that to the surface projection of fault rupture, and 2) epicentral distance and hypocentral distance. The former group seems to be more physically meaningful than the latter, whereas the latter distance measures can be definitely determined with only limited source parameters.

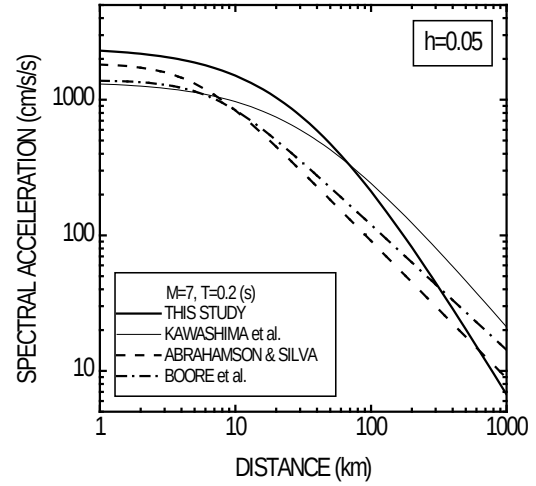
Fig.10 compares our proposed attenuation relation with the previous relationships for $M=7$. Since Kawashima *et al.*⁽⁵⁾ proposed attenuation relations for the three different soil condition classifications that are the same as those given in **Table 1**, we adopt their relationship for the soil condition group-2. The most notable difference between our relation and other relations is that the former gives larger prediction at short distance range. Comparing attenuation rates, our relation falls almost in the middle of previous relationships.

4.2 Acceleration response spectrum

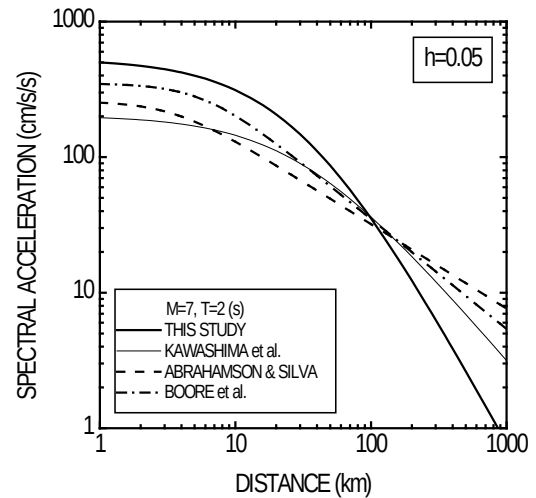
The attenuation relationships developed by Kawashima *et al.*⁽⁸⁾, Abrahamson and Silva⁽²⁴⁾, and Boore *et al.*⁽¹⁵⁾ are compared with our result. Their definitions of attenuation model parameters, which are shown in **Table 9**, differ from ours, however, we do not make compensation for the differences and examine the general trends of attenuation relations, similar to the case of peak ground acceleration.

We assume the following conditions in the comparison of attenuation relationships; we choose the relation for the soil condition group-2 proposed by Kawashima *et al.*⁽⁸⁾. With the Abrahamson and Silva relationship⁽²⁴⁾, we estimate response spectral acceleration from a strike-slip event at a rock or shallow soil site. Regarding the relationship by Boore *et al.*⁽¹⁵⁾, we assume an unspecified mechanism earthquake and the average shear-wave velocity over the upper 30m to be 310 m/s, which is recommended as an average value for soil sites⁽³⁴⁾.

Fig.11 compares the attenuation relations of response spectral accelerations at $T=0.2$ and 2 (s) for $M=7$. The most conspicuous difference between our relation and other relations



(a) $T=0.2$ (s)

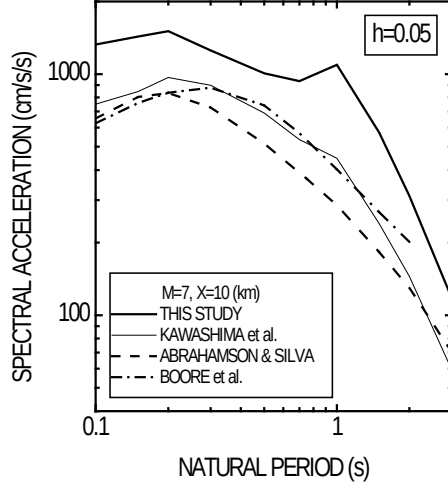


(b) $T=2$ (s)

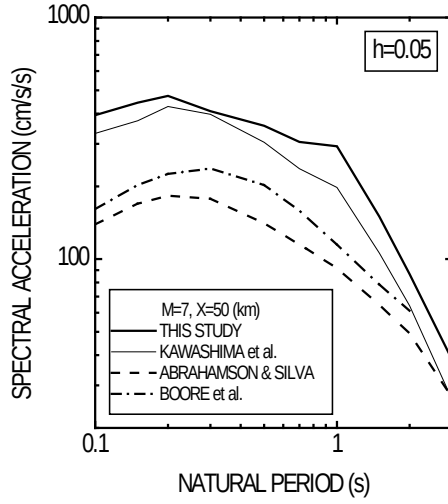
Fig.11 Comparison of attenuation relations for response spectral acceleration ($M=7$)

is that the former yields larger prediction at short distances, and attenuates more rapidly with distance than the latter. These characteristics are observed for the cases of $T=0.2$ and 2 (s) in common.

As an example of predicted response spectrum curves, **Fig.12** illustrates acceleration response spectra for the combinations of $M=7$, and distance $X=10$ and 50 (km). For the short distance, the newly proposed attenuation clearly predicts



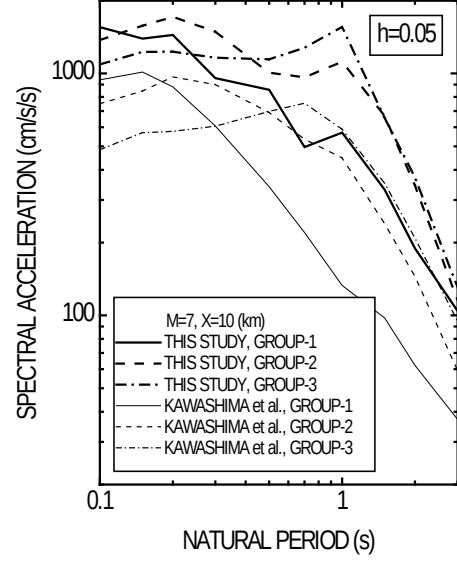
(a) $M=7, X=10$ (km)



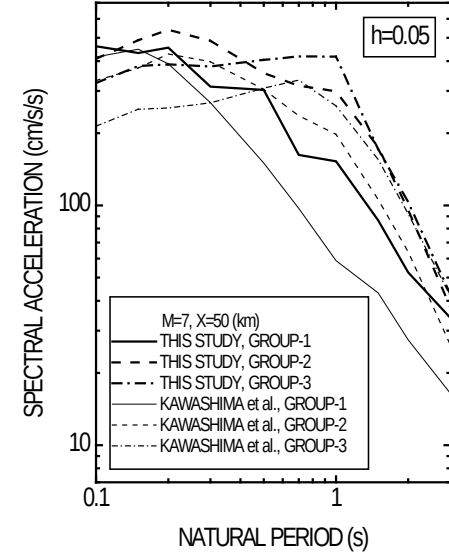
(b) $M=7, X=50$ (km)

Fig.12 Comparison of acceleration response spectra

larger spectral accelerations over all natural period range than the previously proposed relationships, which produce similar level of accelerations, even though we overlook various differences in the definitions of attenuation model parameters. There appears the jaggedness at $T=1$ (s) in the proposed response spectrum curve. This is primarily attributed to a specific combination of earthquake magnitude and distance, and the variation of regression coefficients with natural period. A thorough physical understanding of period-to-period fluctuation in spectral shape would require another detailed study. For the combination of $M=7$ and $X=50$ (km), our attenuation relation still predicts the largest accelerations, however, the relationship by Kawashima *et al.* yields close values to our predictions. Other two models by Abrahamson and Silva, and Boore *et al.* fall below the spectral values predicted by the former two relations except for long natural periods.



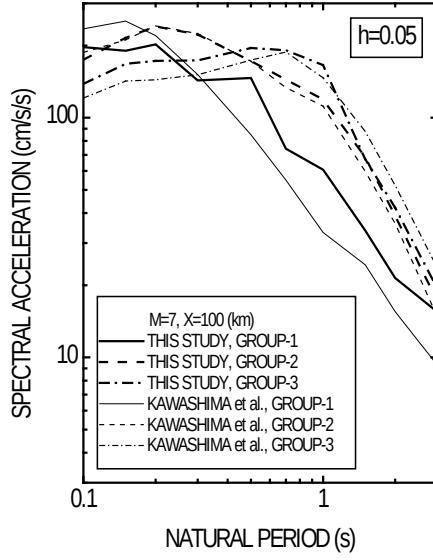
(a) $M=7, X=10$ (km)



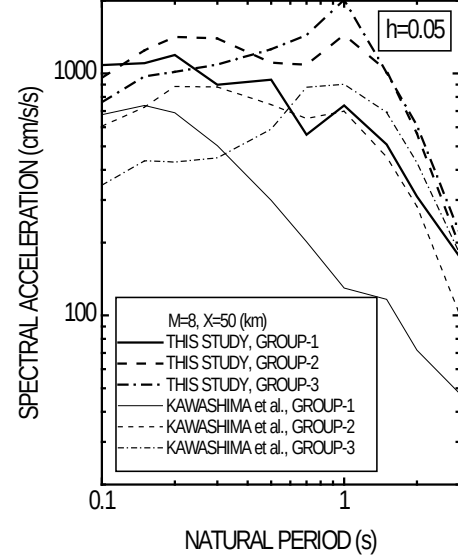
(b) $M=7, X=50$ (km)

Fig.13 (1) Comparison of acceleration response spectra for individual soil condition classifications

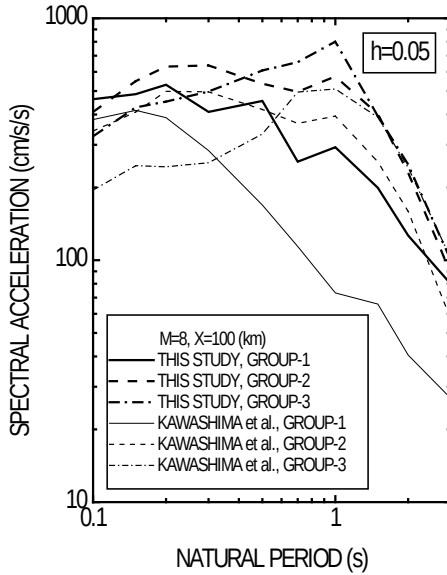
The acceleration response spectra predicted by Kawashima *et al.* are compared in **Fig.13** with our results for individual soil condition classifications. Their attenuation relationships, which were developed by multiple regression analysis of SMAC accelerograph records, are widely applied to engineering practice and form the basis of design seismic load for various structures. Our results are modified for each site soil condition by using the average response spectral acceleration ratio, which is indicated in **Table 7** and **Fig.9**. As easily expected from the descriptions in the previous sections, our proposed attenuation equation predicts larger spectral accelerations than those by Kawashima *et al.* for short distances, e.g., $M=7, X=10$ (km)



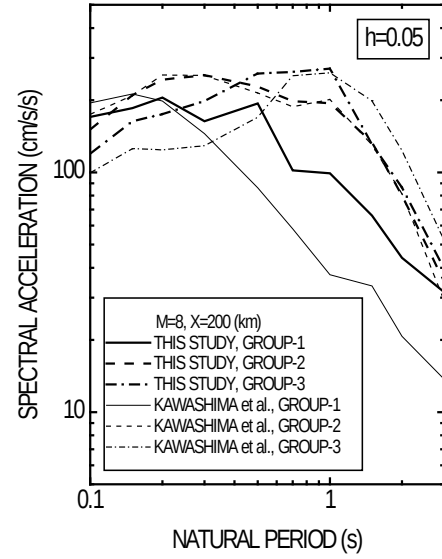
(c) $M=7, X=100$ (km)



(d) $M=8, X=50$ (km)



(e) $M=8, X=100$ (km)



(f) $M=8, X=200$ (km)

Fig.13 (2) Comparison of acceleration response spectra for individual soil condition classifications

and $M=8, X=50$ (km). The response spectrum curves inferred from our model are generally similar in shape to those by their relation for the soil condition groups-2 and 3, while the former produces large spectral amplitudes for the group-1 over the intermediate to long natural period range. It is also noteworthy that there are close resemblances between the response spectra predicted by those two attenuation relationships for certain combinations of earthquake magnitude and distance, such as $M=7, X=100$ (km) and $M=8, X=200$ (km), in spite of the differences that underlie the two formulae, e.g., site condition modification and the strong motion data used for analysis. This is most remarkable with the case of soil condition group-2 followed by that of group-3.

5. Conclusions

We derived a consistent set of attenuation relations for peak ground acceleration and 5% damped response spectral acceleration by means of a two-step stratified regression procedure. Emphasis was placed on presenting simple and practical predictive relations, which are readily applicable to engineering applications. 432 horizontal components of acceleration records from 40 earthquakes including the 1995 Kobe earthquake were employed in this study, and the numerical result was compared with that of the general non-stratified regression analysis and previously proposed

attenuation relationships. We also investigated the influence of soil condition upon the developed attenuation relation, and proposed a method to modify the developed relation by soil condition. The following conclusions may be deduced from the present study.

- 1) Two-step stratified regression analysis produces a larger distance coefficient than the non-stratified regression analysis, which well corresponds with attenuation rates of ground motions computed for individual earthquakes. This technique was verified to be effective for decoupling magnitude and distance, and yield a realistic attenuation relation.
- 2) Comparing with the attenuation relationships that were previously proposed, the newly developed attenuation relation is characterized by predicting large peak ground acceleration or response spectral acceleration at short distances, which seems to be consistent with the recently recorded near-field strong motion data.
- 3) Peak ground accelerations at soil condition group-1 (rock or firm soil) and group-3 (soft soil) sites are smaller, and that at group-2 (medium soil) site is larger than the prediction by the developed attenuation relation without soil condition classification, whereas the average deviations are less than 5 % for all soil classifications. This result suggests that peak ground acceleration is rather insensitive to local soil condition.
- 4) The response spectral acceleration ratio was introduced to examine effects of soil condition on spectral acceleration. The 1-second response spectral accelerations at soil condition group-1 and group-3 sites, for example, are 50% smaller and 40% larger than the prediction without soil condition classification, on an average. The response spectral acceleration ratio proposed in this study may be applicable to modify the developed attenuation relation by soil condition.

Acknowledgments

The authors would like to express their sincere appreciation to various organizations including the former Port and Harbour Research Institute, Japan Metrological Agency, Railway Technical Research Institute and Osaka Gas Corporation for providing valuable strong motion records.

References

- 1) Public Works Research Institute: Study on structural design of Trans-Tokyo Bay Highway, *Rept. of Public Works Res. Inst.*, No. 184, 1991 (in Japanese).
- 2) Honshu-Shikoku Bridge Authority: *Seismic design guideline of Akashi Kaikyo Bridge (Draft)*, 1988 (in Japanese).
- 3) Joyner, W. B. and Boore, D. M.: Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake, *Bull. Seism. Soc. Am.*, Vol. 71, No. 6, 1981.
- 4) Campbell, K. W.: Near-source attenuation of peak horizontal acceleration, *Bull. Seism. Soc. Am.*, Vol. 71, No. 6, 1981.
- 5) Kawashima, K., Aizawa, K. and Takahashi, K.: Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records, *Earthq. Eng. Struct. Dyn.*, Vol. 14, 1986.
- 6) Fukushima, Y. and Tanaka, T.: A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan, *Bull. Seism. Soc. Am.*, Vol. 80, No. 4, 1990.
- 7) Joyner, W. B. and Boore, D. M.: Prediction of earthquake response spectra, *U. S. Geol. Surv. Open-File Rept.*, 82-977, 1982.
- 8) Kawashima, K., Aizawa, K. and Takahashi, K.: Attenuation of peak ground motion and absolute acceleration response spectra, *Proc. 8th World Conf. on Earthq. Eng.*, 1984.
- 9) Annaka, T. and Nozawa, Y.: A probabilistic model for seismic hazard estimation in the Kanto district, *Proc. 9th World Conf. on Earthq. Eng.*, 1988.
- 10) Campbell, K. W.: Strong motion attenuation relations: A ten-year perspective, *Earthq. Spectra*, Vol. 1, No. 4, 1985.
- 11) Kawashima, K., Aizawa, K. and Takahashi, K.: Attenuation of peak ground motions and absolute acceleration response spectra, *Report of Public Works Res. Inst.*, No. 166, 1985 (in Japanese).
- 12) Joyner, W. B. and Boore, D. M.: Measurement, characterization and prediction of strong ground motion, *Proc. Earthq. Eng. Soil Dyn. II*, Am. Soc. Civil Eng., 1988.
- 13) Fukushima, Y.: Survey of recent studies on attenuation relation of strong ground motion (Empirical prediction relation), *Zisin (J. Seism. Soc. Japan)*, Vol. 46, 1993 (in Japanese).
- 14) Iai, S., Kurata, E. and Mukai, K.: An attenuation relation for strong earthquake motions in Japan, *Tech. Note of Port and Harbour Res. Inst.*, No. 724, 1992 (in Japanese).
- 15) Boore, D. M., Joyner, W. B. and Fumal, T. E.: Equations for estimating horizontal response spectra and peak acceleration from western north American earthquakes: A summary of recent work, *Seism. Res. Lett.*, Vol. 68, No. 1, 1997.
- 16) Atkinson, G. M.: Empirical ground motion relations for earthquakes in the Cascadia region, *Can. J. Civil Eng.*, Vol. 24, 1997.
- 17) Campbell, K. W.: Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, *Seism. Res. Lett.*, Vol. 68, No. 1, 1997.
- 18) Campbell, K. W.: Erratum to Campbell, 1997, *Seism. Res. Lett.*, Vol. 71, No. 3, 2000.
- 19) Campbell, K. W.: Erratum to Campbell, 2000, *Seism. Res. Lett.*, Vol. 72, No. 4, 2001.
- 20) Stewart, J. P. et al.: Ground motion evaluation procedures for performance-based design, *Pacific Earthq. Eng. Res. Center Rept.*, 2001/09, Univ. of California, Berkeley, 2001.
- 21) Fukushima, Y.: Revision of attenuation relation and modeling of

- site amplification, *Chikyu Monthly*, Special Issue, No. 37, 2002 (in Japanese).
- 22) Ohno, S. and Takemura, M.: Empirical prediction of strong motion by spectral model, *Chikyu Monthly*, Special Issue, No. 37, 2002 (in Japanese).
 - 23) Ohno, S. *et al.*: Revision of attenuation formula considering the effect of fault size to evaluate strong motion spectra in near field, *Tectonophysics*, Vol. 218, 1993.
 - 24) Abrahamson, N. A. and Silva, W. J.: Empirical response spectral attenuation for shallow crustal earthquakes, *Seism. Res. Lett.*, Vol. 68, No. 1, 1997.
 - 25) Youngs, R. R. *et al.*: Strong ground motion attenuation relationships for subduction zone earthquakes, *Seism. Res. Lett.*, Vol. 68, No. 1, 1997.
 - 26) Atkinson, G. M. and Boore, D. M.: Ground-motion relations for eastern north America, *Bull. Seism. Soc. Am.*, Vol. 85, No. 1, 1995.
 - 27) Si, H. and Midorikawa, S.: New attenuation relationships for peak ground acceleration and velocity considering effects of fault type and site condition, *J. Struct. Constr. Eng.*, Architect. Inst. Japan, No. 523, 1999 (in Japanese).
 - 28) Midorikawa, S., Matsuoka, M. and Sakugawa, K.: Site effects on strong-motion records observed during the 1987 Chiba-ken Toho-oki, Japan earthquake, *Proc. 9th Japan Earthq. Eng. Symp.*, 1994.
 - 29) Kawashima, K., Takagi, Y. and Aizawa, K.: Accuracy of digitization of strong-motion records obtained by SMAC accelerograph, *Proc. Japan Soc. Civil Eng.*, No. 323, 1982 (in Japanese).
 - 30) Kawashima, K., Takagi, Y. and Aizawa, K.: Procedure of instrument correction and displacement calculation for SMAC-B2 accelerograph records with considering accuracy of digitization, *Proc. Japan Soc. Civil Eng.*, No. 325, 1982 (in Japanese).
 - 31) Japan Road Association: *Design specifications for highway bridges, Part V, Seismic design (English edition)*, 2000.
 - 32) Kawashima, K., Aizawa, K. and Takahashi, K.: Effects of composition of two horizontal components on attenuation of maximum earthquake ground motions and response spectra, *Proc. Japan Soc. Civil Eng.*, No. 329, 1983 (in Japanese).
 - 33) Utsu, T.: Relationships between earthquake magnitude scales, *Bull. Earthq. Res. Inst.*, Univ. of Tokyo, Vol. 57, 1982 (in Japanese).
 - 34) Boore, D. M. and Joyner, W. B.: Site amplification for generic rock sites, *Bull. Seism. Soc. Am.*, Vol. 87, No. 2, 1997.

Appendix

List of earthquakes and strong motion records analyzed

Date	Earthquake	M	Recording station	Shortest dist. (km)	Epicentral dist. (km)	Soil class
1/17/67	OFF KINKAZAN	6.3	Kaihoku Bridge		70.6	1
			Date Bridge		144.5	1
			Ofunato Port #1		95.7	3
4/1/68	HYUGANADA	7.5	Ishiseto Bridge	112.4		2
			Myoken Bridge	310.3		3
			Itajima Bridge	79.5		2
			Ariake Dike	220.9		3
			Kochi Port	139.6		3
			Hosojima Port	73.2		2
5/16/68	E OFF AOMORI PREF	7.5	Horoman Bridge		74.0	1
			Muroran Port		184.0	2
			Aomori Port		187.1	3
6/12/68	OFF IWATE PREF	7.2	Kaihoku Bridge		190.9	1
			Aomori Port		254.0	3
			Hachinohe Port		182.7	2
7/1/68	MIDDLE OF SAITAMA PREF	6.1	Shin-Katsushika Bridge	71.0		2
			Shin-Tonegawa Bridge	53.6		2
			Soka Viaduct	64.5		3
			Date Bridge	215.9		1
			Hirai Bridge	72.4		2
			Shitoku Bridge	141.7		2
			Futtsu	102.3		2
			PWRI Chiba Branch #1	90.8		1
			Nishiarai Bridge	67.3		3
			Sakaigawa Bridge	72.0		1
			Ubakubo Bridge	64.0		1
			Haneda Tunnel	79.3		2
			Onahama Port	166.7		2
			Kashima Port #1	123.5		1
			Yokohama Port #2	85.0		2
			Tokyo Port (Shinagawa)	75.8		2
7/5/68	E OFF MIYAGI PREF	6.4	Kaihoku Bridge		78.7	1
			Date Bridge		162.6	1
			Ofunato Port #1		81.9	3
8/6/68	W COAST OF EHIME PREF	6.6	Itajima Bridge	44.3		2
			Hosojima Port	122.5		2
			Kochi Port	109.1		3
9/9/69	MIDDLE OF GIFU PREF	6.6	Shin-Yawata Bridge	81.9		1
			Toyohama Bridge	138.9		2
			Shitoku Bridge	79.7		2
			Nishi-Yokobori Viaduct	186.9		2
			Kinuura Port	89.5		3
			Kobe Port	206.4		2
1/21/70	S PART OF HOKKAIDO	6.7	Kushiro Port		121.6	2
			Muroran Port		177.2	2
			Hachinohe Port		246.7	2
7/26/70	OFF MIYAZAKI PREF	6.7	Ishiseto Bridge	68.2		2
			Hosojima Port	48.8		2
			Kagoshima Port	126.7		3
10/16/70	SOUTHEASTERN AKITA PREF	6.2	Date Bridge	149.7		1
			Yuhei Bridge	17.8		2
			Sakata Port	80.3		2

List of earthquakes and strong motion records analyzed (Cont.)

Date	Earthquake	M	Recording station	Shortest dist. (km)	Epicentral dist. (km)	Soil class
1/5/71	OFF COAST OF AICHI PREF	6.1	Toyohama Bridge		43.6	2
			Shitoku Bridge		150.5	2
			Shin-Tenryugawa Bridge		67.7	3
			Kinuura Port		55.9	3
			Nagoya Port		77.0	2
			Yokkaichi Port		74.3	2
7/23/71	EASTERN YAMANASHI PREF	5.3	Tsurukawa Bridge		15.0	1
			Yokohama Port #1		61.0	3
			Yokohama Port #2		63.7	2
10/11/71	NORTHERN CHIBA PREF	5.2	PWRI Kashima Branch		9.5	2
			Tonegawa Estuary Dam		16.0	3
			Kashima Port #1		13.0	1
12/4/72	E OFF HACHIOJIMA	7.2	Soka Viaduct		312.6	3
			Date Bridge		517.2	1
			Hirai Bridge		301.0	2
			Futtsu		262.0	2
			Kannonzaki		258.8	1
			Onahama Port		416.5	2
			Tokyo Port (Shinagawa)		293.2	2
			Yokohama Port #2		282.7	2
6/17/73	OFF NEMURO PEN	7.4	Kurihama Port		257.6	3
			Tomakomai Port	310.5		2
			Kushiro Port	92.5		2
9/30/73	NEAR CHOSHI	5.9	Muroran Port	364.7		2
			PWRI Kashima Branch		26.9	2
			Kashima Port #2		30.8	3
3/3/74	E OFF CHIBA PREF	6.1	Chiba Port		51.8	2
			Omigawa Bridge		41.3	3
			PWRI Kashima Branch		41.6	2
			Tonegawa Estuary Dam		33.3	3
5/9/74	NEAR S COAST OF IZU PEN	6.9	Kashima Port #2		43.4	3
			Futtsu	114.4		2
			Kannonzaki	106.2		1
			Yokohama Port #1	116.6		3
			Tagonoura Port	48.5		3
7/8/74	OFF IBARAKI PREF	6.3	Omigawa Bridge		81.2	3
			Tonegawa Estuary Dam		79.0	3
			Kashima Port #2		70.9	3
8/4/74	SW IBARAKI PREF	5.8	Shin-Katsushika Bridge		28.3	2
			Shin-Tonegawa Bridge		23.6	2
			Soka Viaduct		25.6	3
			Omigawa Bridge		64.5	3
			Hirai Bridge		34.0	2
			PWRI Chiba Branch #1		45.9	1
			Nishiarai Bridge		31.4	3
			Taira Bridge		145.4	2
			Tonegawa Estuary Dam		73.9	3
			Tokyo Port (Shinagawa)		51.7	2
			Yokohama Port #2		66.3	2
11/16/74	OFF CHOSHI	6.1	Omigawa Bridge		59.2	3
			PWRI Kashima Branch		55.9	2
			Tonegawa Estuary Dam		49.9	3
			Kashima Port #2		53.6	3
2/8/75	NORTHERN CHIBA PREF	5.4	Omigawa Bridge		44.6	3
			PWRI Chiba Branch #2		20.2	1
			Chiba Port		23.3	2
			Tokyo Port (Shinagawa)		44.9	2

List of earthquakes and strong motion records analyzed (Cont.)

Date	Earthquake	M	Recording station	Shortest dist. (km)	Epicentral dist. (km)	Soil class
3/14/75	AICHI-GIFU BORDER	5.3	Shin-Yawata Bridge		33.8	1
			Kinuura Port		45.1	3
			Nagoya Port		24.3	2
			Yokkaichi Port		42.9	2
1/14/78	NEAR OSHIMA	7.0	Kannonzaki	71.8		1
			Numazu Substation	36.5		1
			Atami Substation	36.5		1
			Shin-Iwata Substation	80.9		3
			Shirobori Substation	41.0		1
6/12/78	OFF MIYAGI PREF (Miyagi-ken Oki)	7.4	Shin-Tonegawa Bridge	288.0		2
			Yuhei Bridge	136.1		2
			Kaihoku Bridge	54.6		1
			Taira Bridge	151.4		2
			Ofunato Port #2	78.9		2
3/21/82	S OFF HOKKAIDO (Urakawa-oki)	7.1	Chiyoda Bridge	102.1		2
			Horoman Bridge	33.3		1
			Ishikarikako Bridge	154.7		3
			Hiroo Bridge	54.6		2
			Shimamatsuzawa Bridge	120.9		2
			Sapporo IC Viaduct	139.0		2
3/16/83	S COAST OF CHUBU	5.7	Shin-Yawata Bridge		71.7	1
			Shin-Tenryugawa Bridge		19.2	3
			Hamana Bridge		12.2	2
			Hamanako Bridge		0.6	2
			Toyokawa Bridge		17.9	1
			Fukuroi		26.7	1
5/26/83	W OFF N TOHOKU (Nihonkai-Chubu)	7.7	Takarakaze Bridge	140.8		2
			Yuhei Bridge	152.6		2
			Tsugaru Bridge	81.9		3
			Shichiho Bridge	92.4		1
			Kamitorizaki Bridge	142.0		1
8/8/83	KANTO-CHUBU BORDER	6.0	Kannonzaki		71.1	1
			Nishiarai Bridge		73.7	3
			Sakaigawa Bridge		14.3	1
			Ubakubo Bridge		37.0	1
			Tsurukawa Bridge		13.8	1
			Sakawagawa Bridge		16.7	1
			Yui #2		65.8	2
			Fuji		49.9	1
			JHPC Lab (Machida)		36.3	2
2/14/84	KANTO-CHUBU BORDER	5.2	Sakaigawa Bridge		4.8	1
			Tsurukawa Bridge		4.9	1
			JHPC Lab (Machida)		29.7	2
2/6/87	E OFF FUKUSHIMA PREF	6.7	Omigawa Bridge		167.9	3
			Yoshidagawa Dike		180.7	3
			Tsukinoki Viaduct #1		156.0	2
			Tsukinoki Viaduct #2		156.0	2
4/7/87	E OFF FUKUSHIMA PREF	6.6	Omigawa Bridge		195.4	3
			Yoshidagawa Dike		146.0	3
			Taira Bridge		88.9	2
			Tsukinoki Viaduct #1		126.4	2
			Tsukinoki Viaduct #2		126.4	2

List of earthquakes and strong motion records analyzed (Cont.)

Date	Earthquake	M	Recording station	Shortest dist. (km)	Epicentral dist. (km)	Soil class
4/23/87	E OFF FUKUSHIMA PREF	6.5	Date Bridge		126.9	1
			Yoshidagawa Dike		158.8	3
			Taira Bridge		63.5	2
			Tsukinoki Viaduct #1		130.6	2
			Tsukinoki Viaduct #2		130.6	2
12/17/87	KUJUKURI COAST BOSO PEN (Chiba-ken Toho-oki)	6.7	Shin-Katsushika Bridge	59.8		2
			Yui #1	176.5		2
			Omigawa Bridge	49.9		3
			Futtsu	64.3		2
			Kannonzaki	70.2		1
			Nishiarai Bridge	65.9		3
			Amatsu Bridge #1	46.0		2
			Amatsu Bridge #2	46.0		2
			Ukakubo Bridge	96.6		1
9/5/88	EASTERN YAMANASHI PREF	5.6	Tonegawa Estuary Dam	51.5		3
			JHPC Lab (Machida)		40.8	2
			Futase Dam		49.6	1
			Shin-Sakaigawa Bridge		18.8	1
			Tsurukawa Bridge		17.9	1
2/19/89	SW IBARAKI PREF	5.6	Sakawagawa Bridge		15.2	1
			Shin-Katsushika Bridge		28.4	2
			Omigawa Bridge		66.3	3
			Nishiarai Bridge		31.3	3
10/28/91	SUONADA SETONAIKAI	6.0	Tonegawa Estuary Dam		74.5	3
			Kanmon Bridge (Moji)		19.0	1
			Kanmon Bridge (Shimonoseki)		19.6	1
			Ongagawa Estuary Dam		44.3	2
7/12/93	SW OFF HOKKAIDO (Hokkaido Nansei-oki)	7.8	Nakatsu Estuary Dam		37.7	2
			Tsugaru Bridge	121.8		3
			Shin-Ishikari Bridge	155.6		3
			Shichiho Bridge	72.6		1
			Ishikarikako Bridge	142.8		3
			Isoya Bridge	67.4		3
			Kamitorizaki Bridge	90.8		1
			Sapporo IC Viaduct	148.2		2
1/17/95	SOUTH HYOGO PREF (Hyogo-ken Nanbu)	7.2	Kinokawa Bridge	41.3		2
			Amagasaki Viaduct	9.2		3
			Minato Bridge	105.1		3
			Yodogawa Dike (Hirakata)	26.0		2
			Yamatogawa Dike	31.2		2
			Yoshinogawa Dike (Tokushima)	53.0		3
			Yoshinogawa Dike (Ishii)	57.5		2
			Yodogawa Dike (Oyodo)	15.2		3
			Amagase Dam	43.6		1
			Sarutani Dam	76.2		2
			Yodogawa Estuary Dam	16.5		2
			Kakogawa Estuary Dam	23.4		2
			Kinokawa Dike	39.7		3
			Matsunohama Viaduct P23	29.1		3
			Matsunohama Viaduct P32	29.1		3
			Inagawa	26.0		1
			Yotsubashi	18.2		2
			Kobe Maritime Observatory	0.6		2
			Fukiai	0.7		2
			Takatori	1.8		2