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A NEW ATTENUATION RELATIONSHIP FOR PEAK GROUND ACCELERATIONS DERIVED FROM STRONG-MOTION ACCELEROGRAMS

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SUMMARY

A new attenuation relationship, applicable to the prediction of peak horizontal ground acceleration (PGA) from the near-source region to the far-field, is proposed. The data base consists of 1,372 horizontal components of peak ground accelerations obtained from 43 worldwide shallow earthquakes with magnitude from 4.6 to 8.2. Considering the size effect of rupture zone in the near-source region and the attenuation principle for body-wave in the far-field, the following attenuation relationship is developed.

$$\log_{10}A = 0.41M - 0.0034R - \log_{10}(R + 0.032 \cdot 10^{0.41M}) + 1.30$$

where, A represents a mean of the peak values for the two horizontal components, M is a surface magnitude, and R is a distance from a fault rupture zone. A two-step regression analysis procedure is introduced to avoid interactive effects between the distance and the magnitude coefficients.

INTRODUCTION

Empirical prediction of peak horizontal ground acceleration (PGA) is very important in earthquake engineering. A number of attenuation relationships for PGA, therfore, have been proposed by many researchers.

In order to study the standard attenuation relationship for Japan, we reviewed the relationships proposed within the last 10 years (Tanaka and Fukushima,1987). The distance coefficients of the relationships, as decline, were examined at a distance of 100 km, and compared with those for individual earthquakes. As a result, we found that the former coefficients ranging from 0.6 to 1.9 with the mean of 1.0 were significantly smaller than the latter coefficients of 1.7 on the average (Fig.1). This biased estimates of distance coefficients may be due to the interaction between the distance and the magnitude coefficients caused by non-uniform data-base used in the regression analyses.

On the other hand, the Japanese strong motion data-base contain significantly large number of records from far distant earthquakes. To overcome the shortage of Japanese data at short distances, data observed in the U.S.A. and others can be applied assuming that the source scaling and the attenuation relations are the same for inland earthquakes in Japan and in other countries.

The objective of the present research is to derive a reliable and physically meaningful attenuation relationship for PGA, applicable from the near-source region to the far-field, using a new data-base.

REGRESSION ANALYSIS FOR JAPANESE DATA AND CAUSE OF SMALL DISTANCE COEFFICIENTS

General regression analysis   The comparison of the attenuation relations for the individual earthquakes and that for the whole earthquake as one set is shown in Fig.2, taking a model of the linear attenuation relation in the logarithmic scale as an example. In the analysis, 1,100 mean peak accelerations of two horizontal components from 43 different earthquakes were selected under the conditions that the earthquakes are with Mj (JMA magnitude) ≧6.0 and h (focal depth) ≦30 km, and recorded at many stations. As shown in the figure, the average value of distance coefficients for individual earthquakes was 1.71, while that for the whole data became a significantly smaller value of 1.19 by the multiple regression analysis using the least square method.

Now, let's consider the reason for the difference. The linear regression model is assumed as

$$\log A = aM - b\log X + c \quad \cdots\cdots (1)$$

where X is a hypocentral distance (km), and "a", "b" and "c" are regression coefficients. The magnitude coefficient "a" can be expressed as a linear function of distance coefficient "b" as follows,

$$a = (\sigma_{\log X} / \sigma_M) \cdot R_{M,\log X} \cdot b + (\sigma_{\log A} / \sigma_M) \cdot R_{M,\log A} \quad \cdots\cdots (2)$$

where σ_Y is a standard deviation of Y and $R_{Y,Z}$ is a multiple correlation between Y and Z.

As shown in Fig.3, our data-base has a positive correlation between magnitude and distance, so that the coefficient of "b" is positive. Therefore, if "a" becomes small, then "b" also becomes small. In other words, "b" strongly depends on "a". This may be a reason why most Japanese attenuation formulas have smaller value of the distance coefficient.

Two-step regression analysis   To avoid above mutual correlation between magnitude and distance, a two-step regression analysis using dummy variables, as Joyner and Boore (1981)[1] applied, has been found very effective. At first step, the distance coefficient "b" is assumed to be uniquely assigned for all earthquakes, and determined with the constant term $aM+c$ as "d_i" for each earthquakes. This can be written as,

$$\log A = -b \log X + \Sigma d_i l_i \quad \cdots\cdots (3)$$

where l_is are dummy variables, l_i=1 for ith earthquake and 0 for otherwise, and d_is are coefficients for each earthquake.

Then we obtained "a" and "c" by equation (2). The bold line in Fig.2, shows a result of the two-step regression analysis. We can see a very good agreement with general trend of attenuation relations for individual earthquakes. As shown in Fig.4, the obtained distance coefficient 1.78 almost equals to the mean value 1.71 for individual earthquakes, and it is much larger than the coefficient 1.19 by the general multiple regression. The differences between the general multiple regression and the two-step regression for the typical attenuation models used in Japan are shown in Table 1 and Fig.5.

DATA BASE FOR PRESENT ANALYSIS

The data base consists of 486 Japanese data from shallow earthquakes less than 30 km in depth and with magnitude greater than 5.0, except data of long distances, which are predicted less than 10 Gals, and of 200 the United States' and other countries' data obtained within 50 km from faults, as Campbell (1981)[2] used. The magnitude-distance relation of the data is shown in Fig.6. The hypocentral distance was used for Japanese data, while the fault distance was used for the other foreign data and two very large Japanese earthquakes of the 1968 Tokachi-Oki and the 1983 Nihonkai-Chubu. Japanese magnitude M_j is converted into M_s by the empirical formula proposed by Hayashi and Abe (1984)[3].

MODEL AND PROCEDURE OF REGRESSION ANALYSIS

The following regression model was assumed in this study.

$$\log A = aM - \log(R + c\cdot 10^{aM}) - bR + d \quad \cdots\cdots\cdots\cdots (4)$$

where R is a distance. This model is characterized by the fact that the peak accelerations at short distances approach gradually to an asymptotic value of $-\log c + d$. At the long distance, the model represents the attenuation relation for the body-waves. As shown in Fig.7, the regression analysis using dummy variables was performed twice. First, to extract a true value of "b" and second to stratify the Japanese data and the other data. Since the regression formula is a non-linear, final values of regression coefficients are obtained by iterations. Before the last step was performed, the Japanese data obtained on different ground conditions have been converted to those on the standard ground by station corrections using mean residuals of observed and predicted PGA for each station. Finary, the following formula was obtained.

$$\log A = 0.41M - \log(R + 0.032\cdot 10^{0.41M}) - 0.0034R + 1.30 \quad \cdots\cdots\cdots\cdots (5)$$

The predicted PGAs for $M=7.0$ by this formula are shown in Fig.8 together with the observed data normalized to $M=7.0$. In the figure, the bold and thin lines indicate the attenuation curves for Japan and the United States, respectively. After the station corrections, the standard deviation was improved from 0.32 to 0.20 and the multiple correlation coefficient from 0.68 to 0.83. Acceleration level of the Japanese formula is 50% higher than that of the United States due to mainly the differences of the ground conditions and the frequency characteristics of strong-motion accelerometers. The PGA level at a very close distance to a fault is bounded by 620 Gals regardless of the magnitude. Fig.9 shows the attenuation relationship as a function of magnitude and distance with limits of applicability by lack of the observed data.

DISCUSSION

The new attenuation relationship for PGA is shown in Fig.10 with several other relations proposed in Japan and the United States. It would give more reliable predictions for shorter distances and more reasonable estimates for longer distances than other Japanese relations. As seen in Fig.11, the new attenuation relationship estimates very well the observed data from both interplate and intraplate earthquakes.

The ground conditions at each strong-motion station in Japan can be classified into four types: rock, hard-, medium- and soft-soil grounds. The residuals between the observed and the predicted PGAs and the mean values for each ground condition are shown in Fig.12. From this result, it can be said that the observed PGAs are about 40% smaller at the rock site and about 40% larger at the soft-soil site than those by the predictions, but the differences are insignificant for other soil conditions. Therefore, the site corrections should be necessary to predicted PGA at least for the rock and the soft-soil sites.

ACKNOWLEDGMENT

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2) Campbell, K. W., "Near-Source Attenuation of Peak Horizontal Acceleration", Bull. Seism. Soc. Am. 71, pp.2039–2070, (1981)
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Table 1 Comparison of distance coefficients by non-stratified and two-step stratified regression analysis for typical models in Japan

Model	non-stratified	2-step stratified	Ratio of coefficient	Standard deviation
A	$1.19 \cdot \log X$	$1.78 \cdot \log X$	1.50	0.35
B	$1.50 \cdot \log(\Delta + 30)$	$1.87 \cdot \log(\Delta + 30)$	1.25	0.30
C	$0.00049X$	$0.00164X$	3.35	0.34

A : $\log A = aM - b \cdot \log X + c$

B : $\log A = aM - b \cdot \log(\Delta + 30) + c$

c : $\log A = aM - \log X - b \cdot X + c$

where, A: Peak ground acceleration

M: Magnitude

X: hypocentral distance

Δ: Epicentral distance

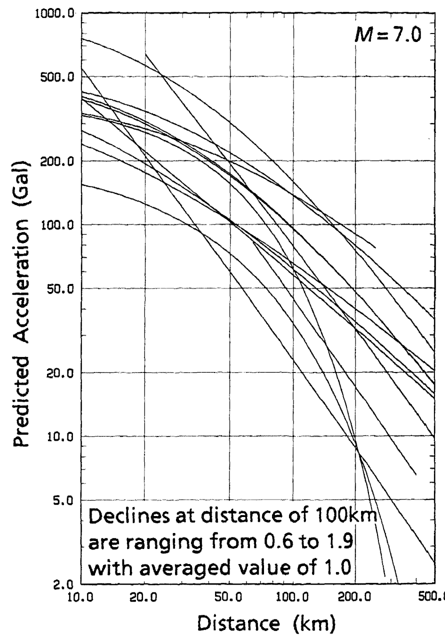

Fig. 1 Attenuation relations for PGA proposed within the last 10 years (1977~1987) in Japan

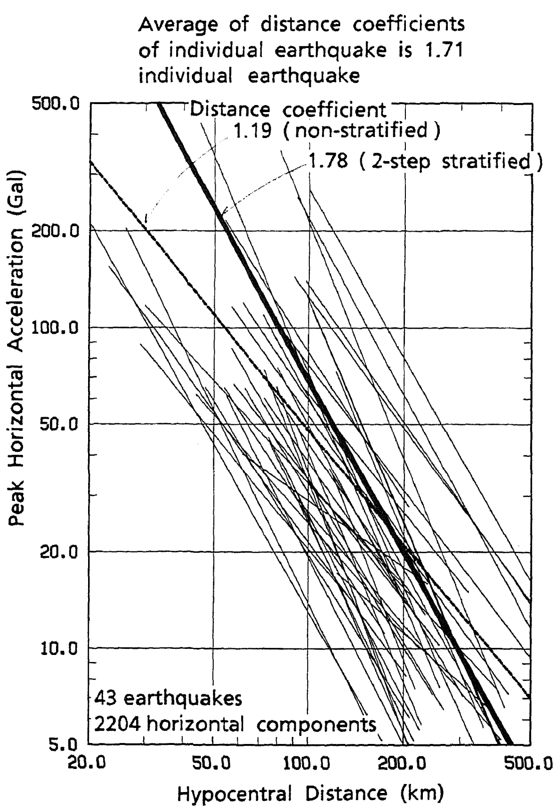

Fig. 2 Comparison of attenuation relationships by non-stratified and two-step stratified regression analyses , and those for individual earthquakes

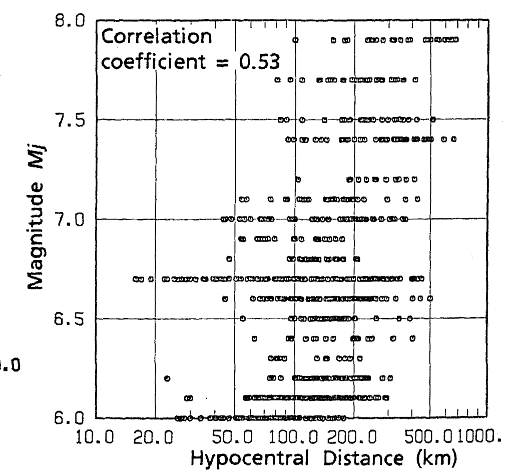

Fig. 3 Magnitude - distance distribution of the data

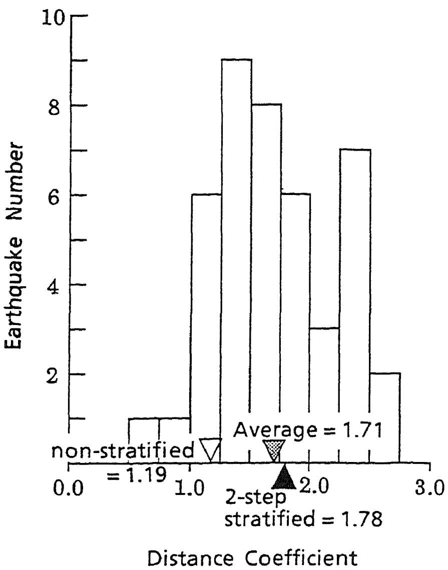

Fig. 4 Histogram of distance coefficients of individual earthquakes. The coefficients by non-stratified and two-step stratified regression analyses are indicated by triangles.

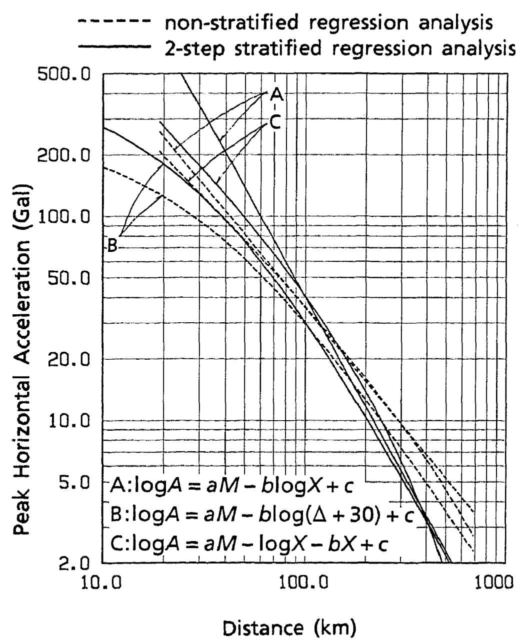

Fig. 5 Comparison of attenuation relationships by non-stratified and two-step stratified regression analyses for typical models in Japan

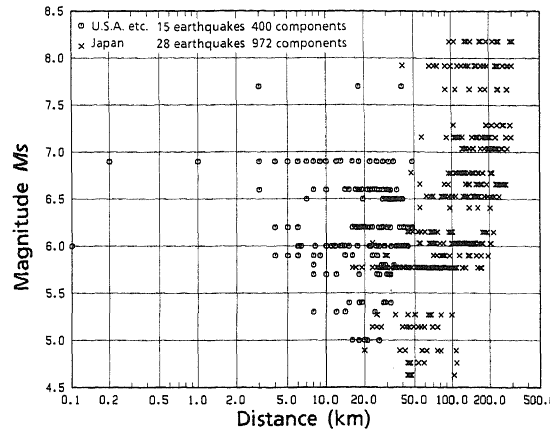

Fig. 6 Magnitude - distance distribution of the data base used in this study

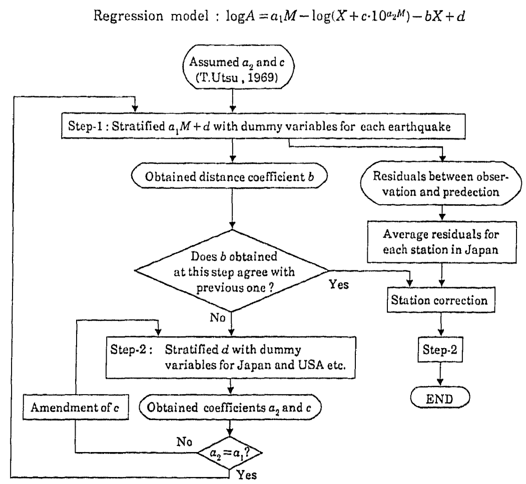

Fig. 7 Procedure of two-step stratified regression analyses

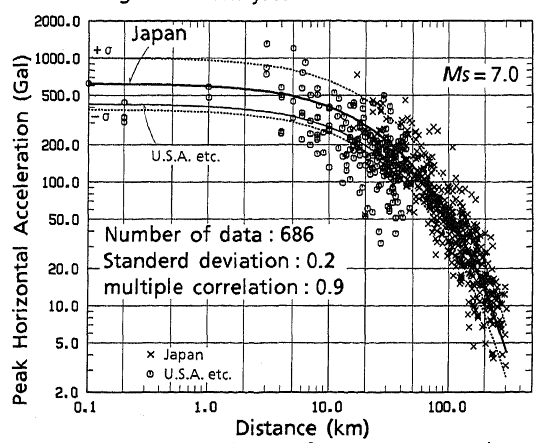

Fig. 8 Comparison of new attenuation relationships for Japan and for U.S.A. etc. with data points normalized to *Ms* 7.0

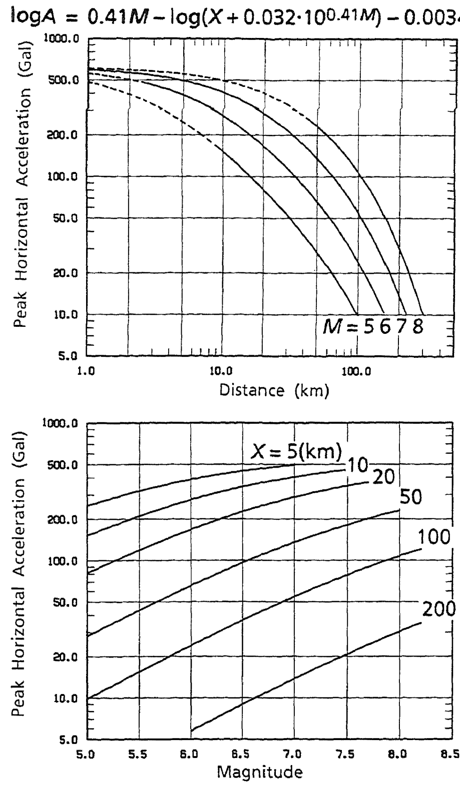

Fig. 9 Predicted PGA by the new attenuation relationships as a function of distance and magnitude

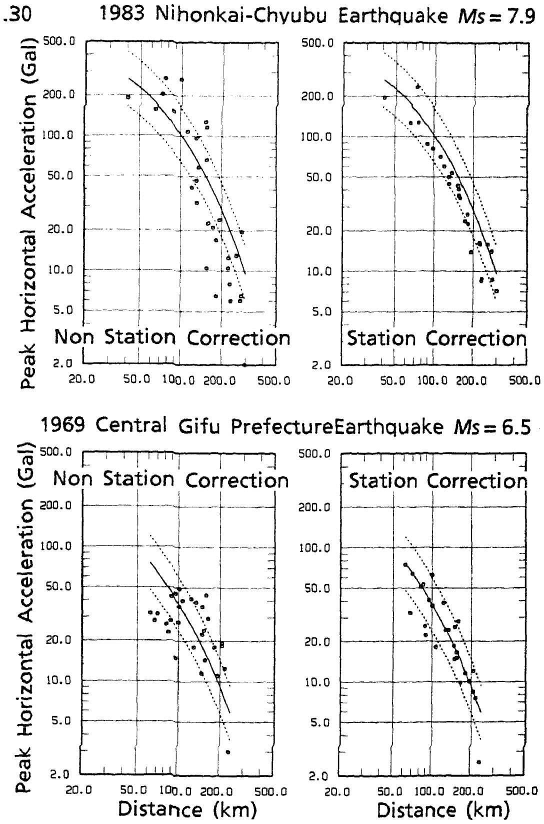

Fig. 11 Comparisons between the observed and predicted PGA

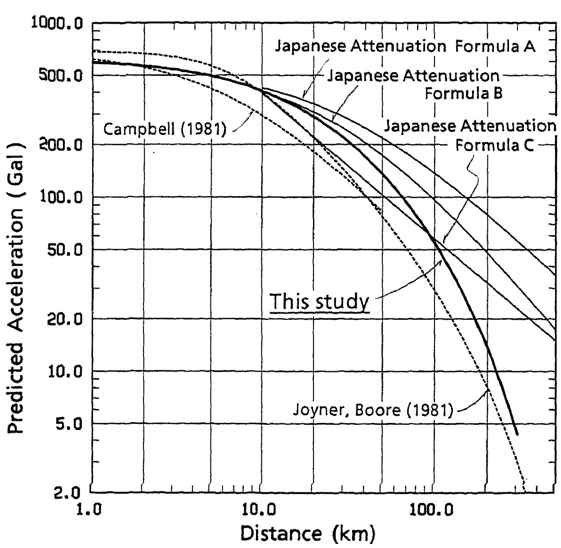

Fig. 10 Comparison of the representative attenuation relationships proposed in recent years with that obtained in this study ($M = 7.0$)

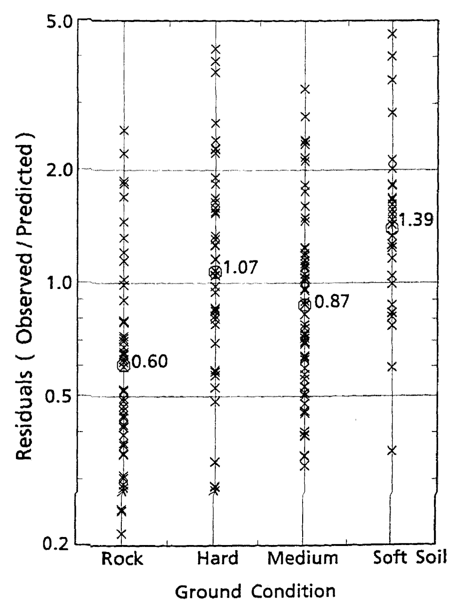

Fig. 12 Distributions of residuals and mean values for each ground condition