COMPARATIVE STUDY ON ATTENUATION CHARACTERISTICS OF GROUND ACCELERATION IN EUROPE, NORTH AMERICA AND JAPAN

by

Fumio YAMAZAKI*

SUMMARY

Using the peak ground acceleration data in Europe, North America and Japan, attenuation characteristics of ground acceleration for shallow earthquakes are investigated. Comparison of the results of one-stage regression and two-stage regression shows that their difference is small for the European and North American data sets. The difference looks large for the Japanese data, but this observation is related to the shortage of near-field data. As long as scarce data is used, the appropriate analysis method seems to be data-dependent. The mean predicted acceleration for Japan is larger than those for Europe and North America. But the reason for this is difficult to pinpoint. Using the European data set and five attenuation models, the effects of data and model selection are also examined. The results show that the levels of standard errors are similar for the different models. The data selection criteria in terms of the minimum magnitude, maximum depth, and source-distance do not affect the results significantly. Further collection of well-examined data is suggested as the most important task for the statistical estimation of earthquake ground motion.

INTRODUCTION

Attenuation of earthquake ground motion is an important topic in earthquake engineering and engineering seismology, especially considering its use in seismic hazard analysis. A large number of attenuation laws have been proposed using various attenuation models and various data from different parts of the world. However, results of these statistical analyses are highly data-dependent. Hence, collection of data and selection of proper data for regression analysis are very important. In this paper, the data characteristics and attenuation characteristics of three peak horizontal acceleration data sets from Europe, North America and Japan are compared.

Recently, Ambraseys and Bommer[1] created a database of strong motion records in Europe and adjacent areas and studied the attenuation of peak ground accelerations[2]. Since this database comprising 529 records from 210 shallow earthquakes is the most comprehensive one for this region, it employed in this study. In North America, a lot of strong motion records exist. Hence data selection becomes an important issue. Joyner and Boore[3] selected 182 records from 23 earthquakes and proposed an attenuation model based on them. Since their model is considered to be a benchmark of attenuation study and several studies used the same data set for model development, we also used it in this study. A large number of records and attenuation models also exist in Japan. However, there are difficulties in collecting appropriate

*) Associate Professor, Institute of Industrial Science, the University of Tokyo

acceleration records in Japan, since 1) observations were made by different organizations and no common database exists; 2) recordings from old instruments require complicated instrument corrections; and 3) the number of records has been increasing rapidly in recent years. Considering these facts, the data set compiled recently by Fukushima and Tanaka[4] is employed in this study. This data set consists of 486 records from 28 shallow earthquakes.

It is noted that theoretical ground motion prediction models[5] based on source parameters and Green's functions received a considerable attention recently. However, such models need detailed source parameters, soil structure modeling and large computational effort. Also, the detailed parameters are usually unpredictable for future events. Hence, the application of these models to seismic hazard analysis is very difficult. Thus, the simple statistical prediction of peak acceleration still bears important roles in practice. But its wide prediction range should be reduced by selecting proper data sets, attenuation models and analysis procedures. It is not an easy task but it is the aim of this study.

GROUND ACCELERATION DATA

Europe

The European data set compiled by Ambraseys and Bommer[1] has 529 records from 219 earthquakes with surface-wave magnitude not less than 4.0 and focal depth not greater than 25 km. Table 1 summarizes the basic characteristics of the data set together with those of North America and Japan. Compared with these regions, European data were originated from various areas of different seismic environments. There are many single-record events (131) since observation stations are less scarce in Europe than in the United States and Japan. Although the number of records is the largest among the three data sets, the European data set includes small magnitude events. If records from less than magnitude 5 events are excluded (the same criterion as the other data sets), the number of records is reduced to 301. Small magnitude events are less reliable in determining the magnitude and source location. Another difference from the other data sets is that the European data set does not exclude the records from the instruments in equal or greater distances from operational but non-triggered instruments. Thus, in far-fields, high-amplitude records might have been preferentially chosen[3].

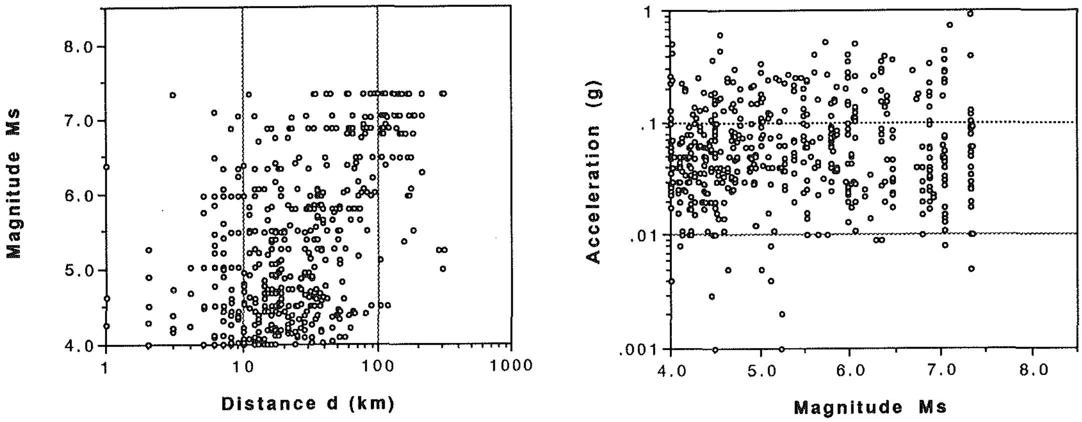
Figure 1 shows the distribution of the 529 data on (a) the distance-magnitude and (b) the magnitude-acceleration plots. A positive correlation between the distance and the magnitude, i.e., small-magnitude events are recorded in short distances and large-magnitude events are recorded in long distances, is seen in Figure 1 (a). In contrast to the Japanese data set, near-source large-magnitude events are also found in the data set. It is interesting to see that there is almost no correlation between the magnitude and observed acceleration (Figure 1 (b)). This may be due to the correlation between the distance and magnitude and the trigger levels of instruments. Hence, removing records from small magnitude events does not necessarily mean removing small acceleration records. Since the determination of the focal depth is not as accurate as the source-to-site distance, the depths were given in 5 km intervals in this data set[1].

North America

The data set compiled by Joyner and Boore[3] comprises 182 records from 23 earthquakes, mostly in California. They selected good data such as those with moment-magnitude not less

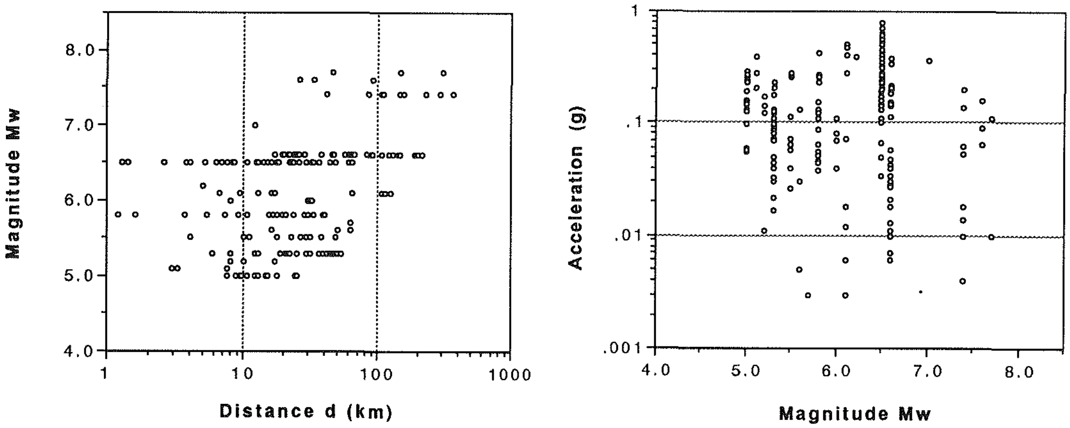
Table 1 Comparison of three databases of peak ground accelerations

Region	Europe	USA	Japan
Researchers	Ambraseys & Bommer (1991)	Joyner & Boore (1981)	Fukushima & Tanaka (1990)
Number of Records	529	182	486
Number of Earthquakes	219	23	28
Singly-Recorded Earthquakes	131	6	no (more than 3 records)
Minimum Magnitude	$M_S \geq 4.0$	$M_W \geq 5.0$	$M_{JMA} \geq 5.0$
Depth	$h \leq 25$ km	($h \leq 20$ km)	$h \leq 30$ km
Minimum Acceleration	Not applied (0.001g)	Smaller distance than non-triggered instrument	Predicted acceleration $\geq$ 0.01g
Recording Station	Free-fields and bases of small structures	Free-fields and bases of 1 or 2 storied buildings	Not specified (free-fields, building bases, bridges, dams)



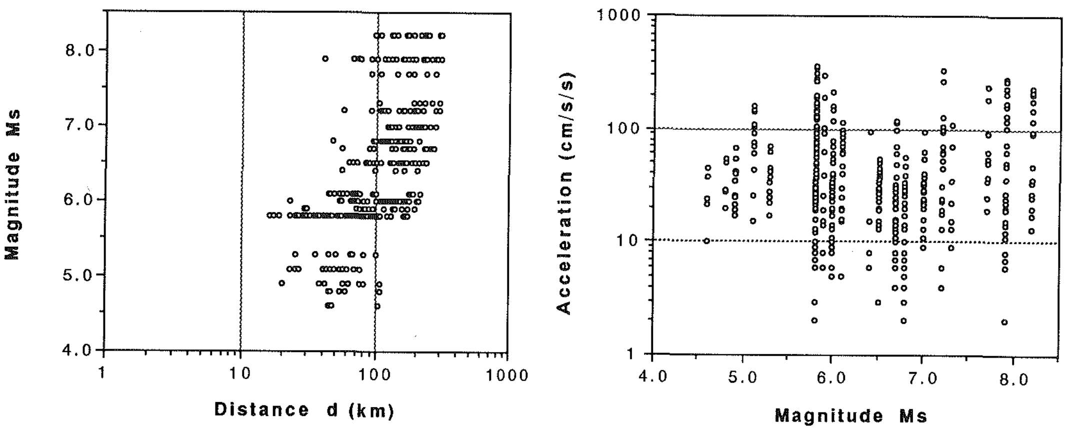
(a) distance-magnitude (b) magnitude-acceleration

Figure 1 Distribution of European acceleration data compiled by Ambraseys and Bommer (1991).



(a) distance-magnitude (b) magnitude-acceleration

Figure 2 Distribution of North American acceleration data compiled by Joyner and Boore (1981).



(a) distance-magnitude (b) magnitude-acceleration

Figure 3 Distribution of Japanese acceleration data compiled by Fukushima and Tanaka (1990).

than 5, estimated accuracy of source-site distance within 5 km, and excluding data recorded at the bases of three or more storied buildings or on the abutments of dams. But the third condition may not be strict enough: the acceleration recorded at the base of a two-storied large building may differ significantly from a free-field one. The depth of each source is not specified, but most are supposed to be less than 20 km. Since this data set was compiled more than ten years ago, a more comprehensive one can be created if records from recent Californian earthquakes (e.g., 1987 Coalinga, 1987 Whittier Narrows, 1989 Loma Prieta) are added.

Figure 2 plots the distribution of the data on the distance-magnitude and the magnitude-acceleration planes. The positive correlation between the distance and magnitude is also seen. Since the data are selected and not so recent ones, the number of data points looks few. Although this data set uses the moment magnitude and the other two use the surface-wave magnitude, their difference is small for the events with magnitudes less than 8.

Japan

There are a lot of earthquake observation stations in Japan, maybe the most in the world. However, as mentioned earlier, constructing a data set for attenuation studies has several difficulties. Since most of the old accelerograms were recorded by SMAC-B2 accelerographs, instrument correction is required to correct suppressed sensitivity in high frequency contents. However, records have only been recently corrected and are rather few. The attenuation law developed by Kawashima et al.[6] used 197 corrected records from 90 earthquakes with focal depths less than 60 km. This data set may be the most complete one for Japan. But the range of the focal depth is too deep compared with the other data sets. Since many Japanese earthquakes occur in subduction zones, they are usually deep. To investigate attenuation characteristics of intermediate and deep earthquakes is one of the important topics for Japan and other subduction zones in the world. But it is not within the scope of this study.

Considering these circumstances, the data set compiled by Fukushima and Tanaka[4] is employed in this study. The data set consists of 486 records from 28 earthquakes with focal depths not greater than 30 km. The data set seems to include uncorrected SMAC records. Unfortunately, this is the only one available for this comparative study. Fukushima and Tanaka used the mean of the two horizontal accelerations to develop the attenuation law in their study. But in this study, the larger of the two horizontal components is used to be consistent with the other two data sets.

Figure 3 shows the distribution of the data on (a) the distance-magnitude and (b) the magnitude-acceleration planes. We can clearly see the shortage of near-field data. Actually, this is the reason why Fukushima and Tanaka included near-field data from Campbell's data list[7] and recent Californian earthquakes for their attenuation study. But this addition is obviously not desirable in constructing an attenuation model for Japan. The focal depths of many events in the data set are not reliable because there are many zero depths[4]. Hence, they are not used in this study.

ATTENUATION MODELS

There are a large number of studies on the attenuation of peak ground acceleration. Although research in this field started long ago, it is only in the last 15 years or so that reliable data were collected to construct attenuation relations. Since a comprehensive summary is found elsewhere[5,8], only a brief description is given here on the five attenuation models used in the analysis hereafter. The models have slightly different forms. But all of them are basically originated from Joyner and Boore[3].

Model 1

Among several attenuation models for peak ground accelerations, one basic form is a linear function of magnitude and two distance-dependent terms:

$$\log a_h = \alpha + \beta M - n_0 \log r + br + \sigma P \tag{1}$$

in which a_h is the maximum horizontal acceleration in g, M is the surface wave magnitude, and r is the slant distance represented by

$$r = \sqrt{d^2 + h^2} \tag{2}$$

in which d is the shortest distance from the surface projection of the fault rupture in km and h is the focal depth in km. This model was used by Ambraseys and Bommer[2] for the European data.

There are four constants, α, β, n_0 and b, in Equation (1). But in this model, n_0, which is a coefficient for geometric losses, is preassigned as a fixed value; 1.0 for spherical spreading from a point source, 0.5 for cylindrical spreading, and 0.0 for plane wave propagation with no spreading. These conditions correspond to far-field, intermediate-field and near-field, respectively. b is a constant for anelastic losses. σ is the standard deviation of $\log a_h$ and the constant P equals 0 for 50 percentiles and 1 for 84 percentiles.

The simplest regression analysis using this model is the ordinary one-stage regression analysis[2], which obtains three constants, α, β and b, at once using a data set comprising a_h, M, d and h. By introducing dummy variables and dividing Equation (1) into two equations, one for distance-dependence and another for magnitude-dependence, the two-stage regression analysis[3] can be also performed. Both the one-stage and two-stage regression analyses are carried out in the examples. However, it has already been shown that their difference is rather small for the European data set[2].

Model 1'

This model is expressed by the equation:

$$\log a_h = \alpha + \beta M - n \log r + br + \sigma P \tag{3}$$

This form is basically the same as Model 1 except that the constant for geometric spreading, n, is also obtained by a regression analysis. Hence, a linear regression analysis is performed for four constants, α, β, n and b, in this model. Since the range of n is not constrained in regression, the obtained n sometimes falls in the inadmissible range ($n > 1$). Both the one-stage and two-stage methods are also possible for this model.

Model 2

This model was proposed by Joyner and Boore[3]:

$$\log a_h = \alpha + \beta M - n_0 \log r' + br' + \sigma P \tag{4}$$

with

$$r' = \sqrt{d^2 + h_0^2} \quad (5)$$

in which h_0 is a constant to be determined with α, β and b. Hence, in this model, the focal depth h of each event is not used for the regression analysis. Instead, h_0 is determined as the one having the smallest σ, which is a sort of averaged focal depth for all the data. Joyner and Boore assumed the spherical spreading (n_0=1) for geometric losses in this format.

The difference between Model 1 and Model 2 is small when d is large. But they exhibit significant difference in the near-field. Although Model 2 cannot consider the depth effect of an individual data point, it is conveniently used in seismic hazard analysis because it does not need to predict the focal depths of future events. When you do not have reliable depth data, you cannot use Model 1 or 1' but you can use this model. Although Joyner and Boore used two-stage regression analysis, one-stage regression analysis is also possible for this model.

Model 2'

This model is expressed by the equation:

$$\log a_h = \alpha + \beta M - n \log r' + br' + \sigma P \quad (6)$$

This form is basically the same as Model 2 except that the constant for geometric spreading, n, is also obtained by regression analysis.

Model 3

This model was proposed by Fukushima and Tanaka[4] for Japanese acceleration data and has the following form:

$$\log a_h = \alpha + \beta M - \log (d + \gamma 10^{\beta M}) + bd + \sigma P \quad (7)$$

There are four constants, α, β, γ and b, in this model. The near source saturation effect is considered with the magnitude-dependent additional distance term proposed by Campbell[7]. The basic difference of this model and the three other models is two-folds: this model approaches a magnitude-independent acceleration value in the near-field while the other models do not, and the focal depth is not considered at all.

Since Equation (6) is a nonlinear function of the coefficients to obtain, some numerical techniques are required to obtain the parameters. Fukushima and Tanaka proposed an iterative procedure for the two-stage regression. A different iterative procedure is employed in this study for the one-stage regression. For an assumed value of γ, three coefficients, α, β and b, are obtained iteratively until two β values in the second and third terms converge. Next, this process is repeated for different values of γ. The set of four parameters which has the minimum σ is considered to be the solution.

This model introduces the strong constraint for near-field acceleration. However, such an assumption has not been justified from actual records (e.g., Boore and Joyner[9]).

RESULTS OF ANALYSIS

Comparison of results of one-stage and two-stage regressions

Since the regression analysis procedure still seems to be a matter of discussion[5,10,11], the results of one-stage and two-stage regression analyses are compared for the three data sets.

Note that when either one-stage or two-stage regression is used, a weight for each record is an influential factor to the result. For one-stage regression, Campbell[7] proposed a weighting scheme based on the distance range. Other weighting schemes, e.g. giving equal weight to each earthquake, are also possible. The selection of an appropriate weighting scheme is data-dependent. If a data set contains well-balanced data in terms of the number of records in each event, the source-site distance, the magnitude, etc., weighting is not necessary. Since three data sets are used in this study, a simple equal weight is assigned to each record in one-stage regression analysis. In this case, we must be careful that earthquakes with many records highly influence the result.

There are several weighting schemes[3,4,11] for two stage-regression. It may take some time until agreement is made among researchers. In this paper, the weighting scheme proposed by Joyner and Boore[3] in 1981 is employed. In this method, an equal weight is given to each record in the first-stage regression for distance dependence, and an equal weight is assigned to each earthquake excluding single-record events in the second-stage regression for magnitude dependence.

Tables 2 to 4 and Figures 4 to 6 show the results of the one-stage and two-stage regression analyses for the three data sets. For the European and North American data sets, the results of the two methods were found to be very close. Note that in the two-stage regression, the standard deviations are obtained for each step. Hence, they are not comparable to that of the one-stage regression. Figure 5, which compares typical predicted mean curves of one-stage and two-stage regressions for the North American data, give practically the same results for the two methods. For the European data set, a significant difference between the two methods is observed only for Model 2' in the near-field. But this difference is only due to the difference of the optimum h_0 values obtained by the two methods. Actually, these values are not so decisive because the standard error is very insensitive to the change of h_0.

In contrast to these observations, the results for the Japanese data look quite different for the two methods. Since the depth data were not so reliable for the Japanese data, Models 2 and 2', which do not use depth data, were employed. In these models, the optimum h_0 values, which give the minimum standard error, were sought. But the one-stage regression for Model 2 and the two-stage regression for Model 2' could not find the converged h_0 (see Table 4). Although zero depth ($h_0 = 0$) gave the minimum standard error, it is not an adequate solution. However, the one-stage regression for Model 2' and the two-stage regression for Model 2 gave reasonable h_0 values. These facts indicate that the Japanese data set is not enough to determine near-field attenuation characteristics due to the lack of near-field data. Actually this is the reason why Fukushima and Tanaka[4] added the data from other regions when they developed the Japanese attenuation law covering the near-field. Hence, for the Japanese data set, it is difficult to discuss the difference of one-stage and two-stage regressions.

It is true, as Fukushima and Tanaka[4] emphasized, that the multicollinearity problem occurs if supposedly independent data (e.g., distance and magnitude) are actually correlated. Hence, the two-stage regression is theoretically preferable when ample observations exist for each event. But the selection of method is data-dependent. As demonstrated above, their difference is not always large.

Comparison of attenuation relations from three data sets

The results of two-stage regression analysis for the three data sets are compared in Figure

Table 2 Comparison of coefficients of attenuation formula obtained by one-stage and two-stage regression analyses for European data (Ambraseys and Bommer, 1991)

Method	Model	α	β	b	n	h_0	σ_1	σ_2	σ
one-	#1	-0.87	0.217	-0.00117	1.0				0.263
stage	#2	-1.09	0.238	-0.00050	1.0	6.0			0.278
	#2'	-1.28	0.233	-0.00138	0.84	3.9			0.277
two-	#1	-0.89	0.211	-0.00084	1.0		0.253	0.186	0.314
stage	#2	-1.17	0.239	-0.00004	1.0	3.3	0.245	0.227	0.334
	#2'	-1.36	0.230	-0.00124	0.81	1.3	0.244	0.224	0.331

Underline means an assigned value.

Table 3 Comparison of coefficients of attenuation formula obtained by one-stage and two-stage regression analyses for North American data (Joyner and Boore, 1981)

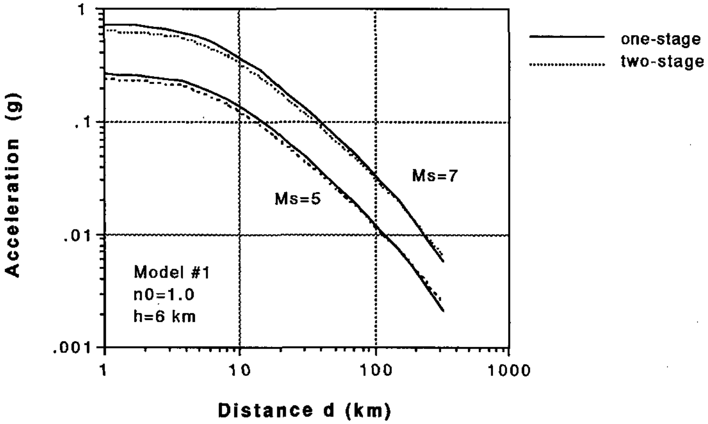
Method	Model	α	β	b	n	h_0	σ_1	σ_2	σ
one-	#2	-1.03	0.248	-0.00196	1.0	6.6			0.249
stage	#2'	-0.50	0.261	-0.00033	1.41	11.3			0.247
two-	#2	-1.02	0.249	-0.00255	1.0	7.3	0.222	0.132	0.258
stage	#2'	-0.42	0.270	-0.00089	1.48	12.8	0.220	0.143	0.262

Underline means an assigned value.

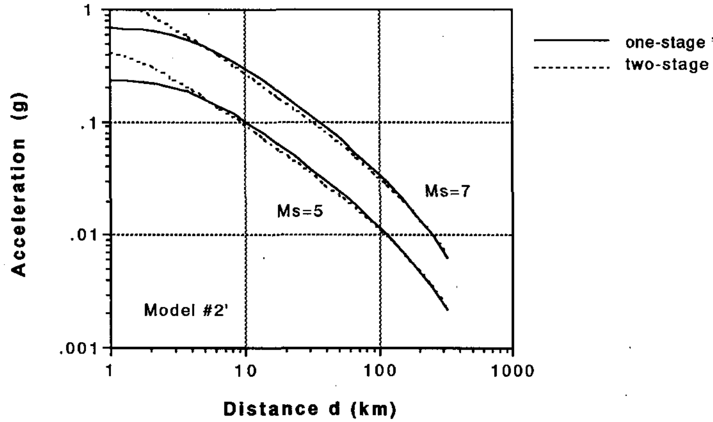
Table 4 Comparison of coefficients of attenuation formula obtained by one-stage and two-stage regression analyses for Japanese data (Fukushima and Tanaka, 1990)

Method	Model	α*	β	b	n	h_0	σ_1	σ_2	σ
one-	#2	1.91	0.283	-0.00183	1.0	0.0			0.313
stage	#2'	2.56	0.287	-0.00073	1.39	20.0			0.313
two-	#2	1.78	0.335	-0.00291	1.0	14.0	0.280	0.166	0.326
stage	#2'	1.50	0.332	-0.00337	0.83	0.0	0.280	0.166	0.326

Underline means an assigned value. * Unit of acceleration is cm/s^2.

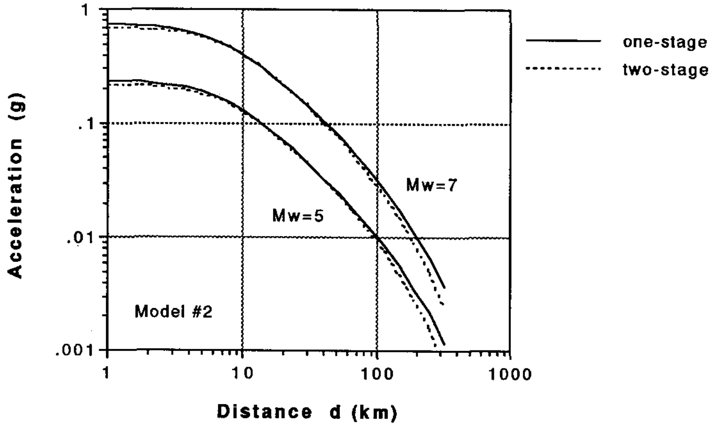


(a) Model 1 when *h*=6 km

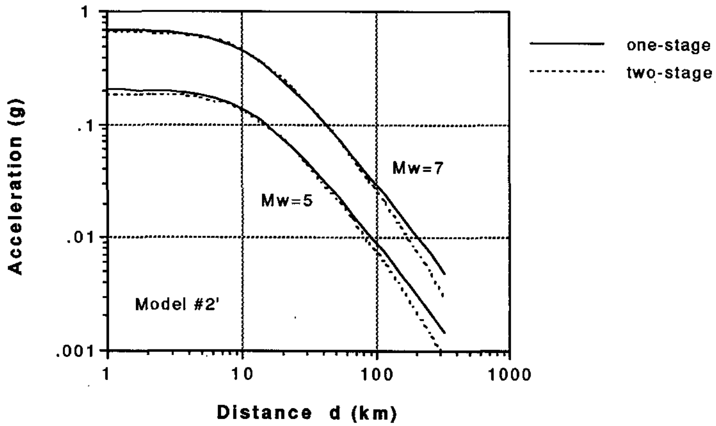


(b) Model 2'

Figure 4 Predictive curves of mean peak horizontal acceleration for European data by one-stage and two-stage regressions.

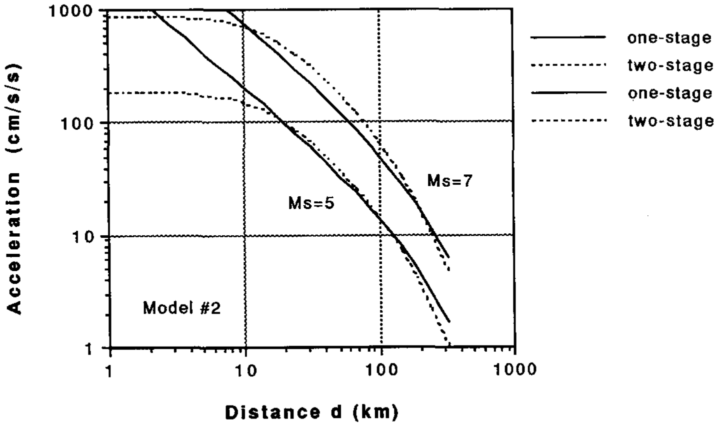


(a) Model 2

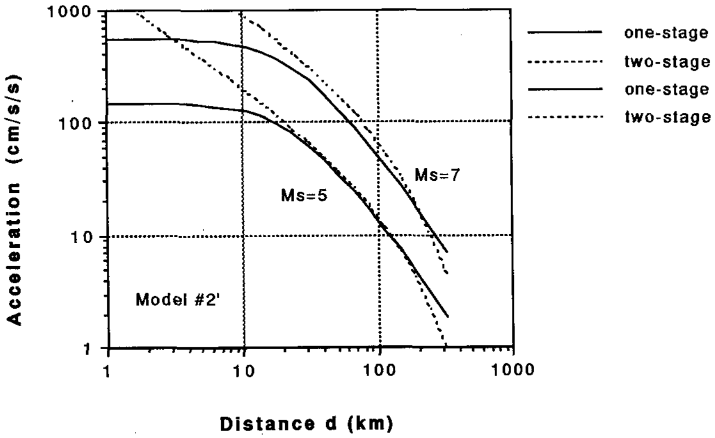


(b) Model 2'

Figure 5 Predictive curves of mean peak horizontal acceleration for North American data by one-stage and two-stage regressions.

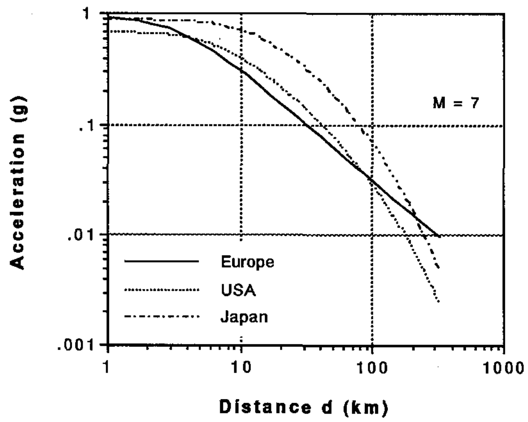


(a) Model 2

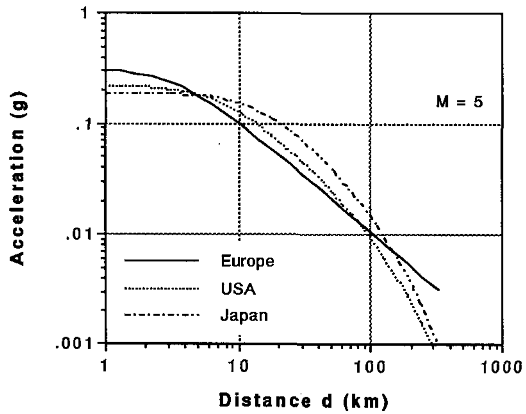


(b) Model 2'

Figure 6 Predictive curves of mean peak horizontal acceleration for Japanese data by one-stage and two-stage regressions.



(a) M=7



(b) M=5

Figure 7 Predictive curves of mean peak horizontal acceleration for three databases by two-stage regression (Model 2).

7. The figure shows only the results for Model 2 because for Model 2', geometric loss coefficient was inadmissible (n >1) for the North American data and h_0 was not obtained properly for the Japanese data set. The general trend of the attenuation curve looks similar for the North American and Japanese data sets while the European data set exhibits larger attenuation in the near-field and smaller attenuation in the far-field. Several reasons for this discrepancy can be considered: 1) h_0 value for Europe was much smaller than for the others, which explains the large attenuation rate in the near-field; 2) a very small anelastic loss coefficient (b) was obtained for Europe, which explains the low attenuation rate in the far-field; 3) far-field data are potentially overestimated for the European data set since the cut-off scheme based on non-triggered instruments was not employed. But except for the very near-field and far-field (e.g., d=5 km to 100 km), the mean predicted accelerations for Europe and North America are rather close.

On the other hand, the predicted acceleration for Japan in this intermediate range looks larger than those for the other regions. Fukushima and Tanaka derived the same result between the Japanese and American data. The possible reasons for this discrepancy are differences in soil conditions, instruments and fault mechanism, etc. Since the attenuation models employed do not consider soil conditions and there are a lot of soft-soil recording stations in Japan, difference in soil conditions may be the most probable reason. As stated earlier, most old Japanese records need instrument correction and the Japanese data used here seem uncorrected. If we use corrected records, however, the discrepancy may become larger because high-frequency contents would be magnified. Conversion of magnitude scale from Japan Meteorological Agency (JMA) to surface-wave may also include error to some extent. However, further research is necessary to pinpoint the reason for the discrepancy.

Together with the mean predicted acceleration, the standard error of regression analysis is an important factor in comparing the data sets. As seen in Tables 2 to 4, the North American data have the smallest standard errors for both the one-stage and two-stage regressions although it has the smallest number of data. This may be explained by the fact that the North American data are selected ones and came from similar seismic environments. The standard errors for European and Japanese data are almost in the same level. It is interesting to see that the standard error for the first-stage regression (distance-dependence) is larger for Japanese data while that for the second-stage regression (magnitude-dependence) is larger for European data. These observations may be explained as follows: 1) since many earthquake sources in Japan are located in the sea, the estimation of source locations may be less accurate in Japan than in the other regions; 2) since European data include small magnitude events, the estimation of magnitude in the European data may be less accurate than in the other data.

Effect of minimum magnitude for European data

As a first sensitivity study on data selection, effects of the minimum magnitude are examined for the European data set. By selecting records from the earthquakes with $M \geq 5$, the number of records is reduced to 301. For earthquakes with $M \geq 6$, the number of records becomes 152. Table 5 summarizes the results of regression analysis for these three data sets with different minimum magnitudes. Coefficients were calculated for five attenuation models by the one-stage regression analysis. For all these attenuation models, the standard error becomes smaller as the minimum magnitude increases. But the number of data decreases. Thus, we must consider these two facts in determining the minimum magnitude to use. Since the acceleration level is almost independent of the magnitude (Figure 1 (b)), the difference in the standard errors may come from the error when determining the magnitude for small magnitude events.

For the European data, the difference of the standard errors between the last two data sets is small. Hence, the use of minimum magnitude M=5 is suggested for the European data. Actually, this is the same criterion used by Joyner and Boore[3] for the North American data and Fukushima and Tanaka[4] for the Japanese data. It was found that the mean regression lines for the three data sets (with the different minimum magnitudes) were found to be very close although they gave somewhat different parameter values (Table 5).

Comparison of attenuation models for European data

The standard errors for Model 1 shown in Table 5 indicate that the current data set is better expressed by spherical spreading (n_0=1) than cylindrical spreading (n_0=0.5) or plane wave propagation (n_0=0). Figure 8 (a) compares predicted curves of mean peak acceleration for these three geometric spreading constants in Model 1. Large differences are observed among them especially in the distances $d \leq 20$ km and $d \geq 200$ km. The results for Model 1' (Table 5) show that the value of n with minimum σ is in the range of 1.1−1.3 for the current data sets. However, such values of n (>1) is physically inadmissible. Note that in these cases, the values of b are also physically inadmissible (b >0). It is interesting to see that, in contrast to Model 1', reasonable values of n and b are obtained for Model 2'.

It is seen in Model 1 that by reducing the geometric spreading constant n, the anelastic attenuation constant b decreases accordingly. This indicates that these two coefficients are highly dependent. Thus, the optimum values of n and b are sometimes obtained as physically inadmissible values (n greater than 1 or b greater than 0). Although the attenuation models having the geometric spreading and anelastic loss terms are well explained by the wave propagation theory, it is difficult to determine the two distance-dependent terms simultaneously, as pointed out by Joyner and Boore[12]. One possible reason is that the number of data points is not large enough and they are not well-distributed. Another reason is that these coefficients are distance-dependent: anelastic losses are large and geometric losses are small in the near-fields, and vice versa in the far-fields. Actually, this is the limitation of a simple regression analysis which estimates a set of parameters covering all the data ranges. Also, it may be considered that peak acceleration is a rather random quantity governed by short period contents and, hence, cannot be expressed well by just the magnitude (which is determined by much longer period contents) and distance.

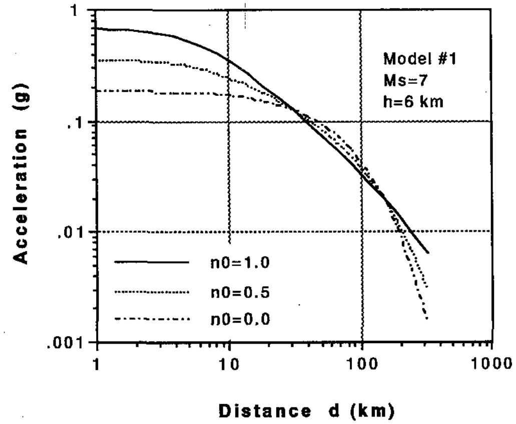
Since the predicted acceleration by Model 1 is depth-dependent, Figure 8 (b) plots the predicted mean curves for three focal depths. The model exhibits different expected accelerations in the near-fields. However, this model seems to overestimate the depth effects. This view comes from the fact that vertical separation exhibits less attenuation than horizontal separation due to smaller damping in deep portions of the crust. This can be validated by the observation that the identified h_0 value is much smaller than the averaged focal depth of all the events. If we use a slant distance to the source in attenuation format, a depth-adjusting term[13] may be required to reduce the depth effect.

It is noted that for the data sets of $M \geq 5$ and $M \geq 6$, the three models show almost the same values of σ. Hence, it is difficult to discuss which model is superior for the European data set. Figure 9 compares the predicted curves of mean peak accelerations derived for the four

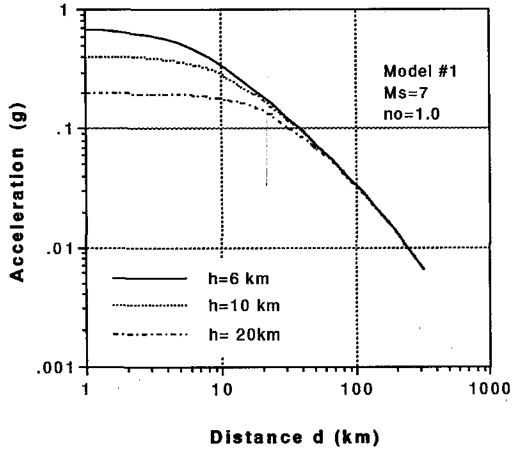
Table 5 Coefficients of attenuation formula obtained by one-stage regression analysis for European data for $h \leq 25$km

Data set	Model	α	β	b	n	h_0	γ	σ
$M_s \geq 4.0$ N=529	#1	-0.87	0.217	-0.00117	1.0			0.263
		-1.41	0.203	-0.00423	0.5			0.285
		-1.95	0.189	-0.00730	0.0			0.323
	#1'	-0.57	0.225	♦ 0.00060	1.29			0.259
	#2	-1.09	0.238	-0.00050	1.0	6.0		0.278
	#2'	-1.28	0.233	-0.00138	0.84	3.9		0.277
	#3	-1.29	0.288	-0.00114	1.0		0.117	0.281
$M_s \geq 5.0$ N=301	#1	-0.80	0.203	-0.00095	1.0			0.242
		-1.29	0.179	-0.00379	0.5			0.263
		-1.78	0.155	-0.00662	0.0			0.304
	#1'	-0.61	0.217	♦ 0.00013	1.12			0.241
	#2	-1.10	0.241	-0.00053	1.0	6.0		0.242
	#2'	-1.20	0.237	-0.00096	0.91	4.8		0.242
	#3	-1.27	0.276	-0.00088	1.0		0.080	0.244
$M_s \geq 6.0$ N=152	#1	-0.98	0.225	-0.00062	1.0			0.238
		-1.59	0.220	-0.00352	0.5			0.256
		-2.20	0.215	-0.00643	0.0			0.294
	#1'	-0.83	0.226	♦ 0.00006	1.19			0.238
	#2	-1.15	0.242	-0.00024	1.0	5.3		0.236
	#2'	-1.27	0.239	-0.00077	0.90	3.9		0.237
	#3	-1.26	0.265	-0.00051	1.0		0.055	0.238

Underline means an assigned value. ♦ indicates a physically inadmissible sign.

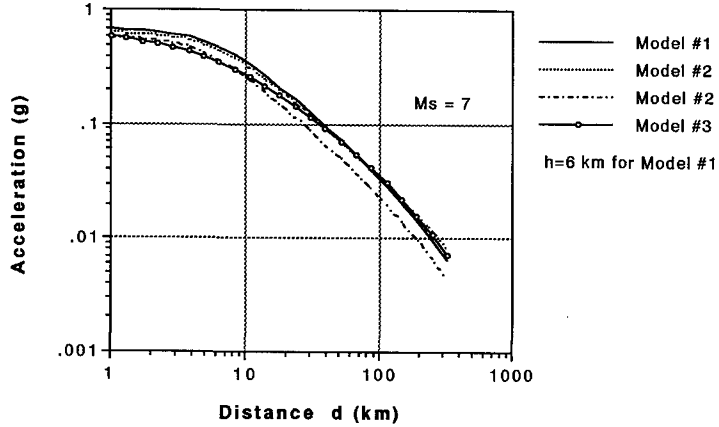


(a) for different spreading constants

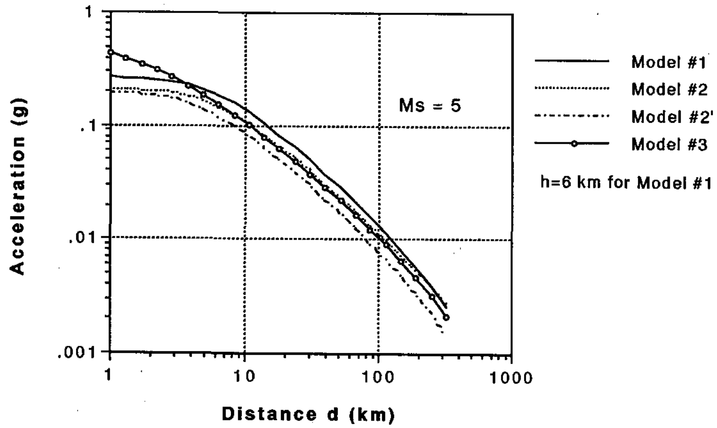


(b) for different focal depths

Figure 8 Predictive curves of mean peak horizontal acceleration by one-stage regression for Model 1 (European data set for $M \geq 5$).



(a) M=7



(b) M=5

Figure 9 Predictive curves of mean peak horizontal acceleration by one-stage regression for four models (European data set for $M \geq 5$).

models. In this figure, the curve for Model 1 is plotted for h=6 m, which is the depth identified by Model 2. These four curves are found to be very close but Model 3 predicts higher acceleration in the near-field for small magnitude. But this is due to the constraint (the magnitude-independent acceleration value in the near-field) forced on Model 3. Except for this difference, all the mean predicted curves are within the range (between 1/1.74 and 1.74 times) calculated from their standard errors (about 0.24 for all the models, hence, $10^{0.24}$=1.74). Thus, the differences among the models are not significant compared with the variation of each data.

Effects of data selection in terms of depth and distance for European data

A regression analysis was also conducted for earthquakes whose focal depths are not greater than 15 km. The two data sets, $M \geq 4$ and $M \geq 5$, were used in the analysis. No significant change is observed when it is compared with Table 5 for $h \leq 25$ km. The standard errors become slightly smaller for the data set of $M \geq 4$. However, for the data set of $M \geq 5$, the result is almost the same as that in Table 5. We had expected some reduction of h_0 value by Model 2 because it is a kind of averaged focal depth for the data used. However, the estimated h_0 value was almost unchanged.

To examine attenuation characteristics of accelerations in near-fields, data points satisfying the condition $r \leq 2L$ were selected. Here, r is the slant distance defined by Equation (2), and L is the source length estimated by $\log L = 0.7M - 3.28$ (Ambraseys and Melville[14]). Only 90 data were selected by applying this condition. Regression analysis was conducted for Models 1, 1', 2 and 2'. For Models 1' and 2', we had anticipated a small value of n and small (negative) value of b because geometric losses should be small and anelastic losses are large in the near-fields. However, the results were disappointing; n was large and b was even positive. Models 1 and 2 also showed larger standard errors for smaller values of n_0. These results again indicate the difficulty of obtaining proper parameter values for the model with two distance-dependent terms, especially when data are not enough.

CONCLUSION

Attenuation characteristics of peak horizontal acceleration were studied using the ground acceleration data from shallow earthquakes in Europe, North America and Japan. Four attenuation models with a magnitude independent shape and one attenuation model with a magnitude dependent shape were employed. Both geometric losses and anelastic losses were considered in these models as distance-dependent terms. First, the results of one-stage regression and two-stage regression were compared for the three data sets. The results of the two methods are close for the European and North American data while they show some difference for the Japanese data, indicating the data-dependency of the appropriate method.

A depth-independent model was used to compare the attenuation laws from the three data sets since this is the only case in which reasonable results were obtained for all the data sets. The models derived for Europe and North America were in similar levels except for the very near-field and far-field. The discrepancy in these regions can also be explained. The model for the Japanese data, however, shows higher acceleration than those for the other two. Several reasons can be considered to explain the difference, but it is difficult to pinpoint which one.

Effects of data selection were also examined using the European data in terms of the minimum magnitude, the focal depth and the source distance. Considering both the number of data and the standard error of the regression analysis, minimum magnitude M=5 was recommended for this data set. The results of regression analysis were almost the same for the data set of focal depth $h \leq 25$ km and that of $h \leq 15$ km, indicating insensitivity of the results to the focal depth for this range of shallow events. A regression analysis was also performed for only near-field data. However, expected large anelastic losses and small geometric losses were not obtained The mean predicted accelerations and standard errors were close for the five models for the European data.

All these analysis results suggest that the collection of good-quality data is the most important issue in the statistical prediction of earthquake ground motion. Although the choice of a proper analysis method and a proper functional form affects the results, the proper choice itself is data-dependent when available data are scarce.

ACKNOWLEDGMENT

This work was conducted during the author's stay at Imperial College, London, England from March to September of 1992. The author expresses his appreciation to Professor N. N. Ambraseys for helpful comments. The Japanese acceleration data set used in this study was provided by Mr. Y. Fukushima of Ohsaki Research Institute, Shimizu Corporation, Japan.

REFERENCES

1. N. N. Ambraseys and J. J. Bommer, "Database of European earthquake associated with strong-motion records", European earthquake eng. V, No.2 , 18-37 (1991).
2. N. N. Ambraseys and J. J. Bommer, "The attenuation of ground accelerations in Europe", Earthquake eng. struct. dyn. **20**, 1179-1202 (1991).
3. W. B. Joyner and D. M. Boore, "Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake", Bull. seism. soc. Am. **71**, 2011-2038 (1981).
4. Y. Fukushima and T. Tanaka, "A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan", Bull. seism. soc. Am. **80**, 757-783 (1990).
5. W. B. Joyner and D. M. Boore, "Measurement, characterization and prediction of strong motion", Proc. ASCE Conf. earthquake eng. soil dyn., Park City, Utah, 43-102 (1988).
6. K. Kawashima, K. Aizawa, and K. Takahashi, "Attenuation of peak ground acceleration, velocity and displacement based on multiple regression analysis of Japanese strong motion records", Earthquake eng. struct. dyn. **14**, 199-215 (1986).
7. K. W. Campbell, "Near-source attenuation of peak horizontal acceleration", Bull. seism. soc. Am. **71**, 2039-2070 (1981).
8. K. W. Campbell, "Strong motion attenuation relations: A ten year perspective", Earthquake Spectra, Vol. 1, No. 4, 759-804 (1985).
9. D. M. Boore and W. B. Joyner, "The empirical prediction of ground motion", Bull. seism. soc. Am. **72**, S43-S60 (1982).
10. D. R. Brillinger and H. K. Preisler, "Further analysis of the Joyner-Boore attenuation data", Bull. seism. soc. Am. **75**, 611-614 (1985).
11. T. Masuda and M. Ohtake, Comment on "A new attenuation relation for peak horizontal acceleration of strong earthquake ground motion in Japan" by Y. Fukushima and T. Tanaka, Bull. seism. soc. Am. **82**, 521-522 (1992).

12. W. B. Joyner and D. M. Boore, Comments on "New attenuation relations for peak accelerations of strong motion" by B. A. Bolt and N. A. Abrahamson, Bull. seism. soc. Am. **73**, 1479-1480 (1983).

13. C. B. Crouse, Y. K. Vyas and B. A. Schell, "Ground motions from subduction-zone earthquakes", Bull. seism. soc. Am. **78**, 1-25 (1988).

14. N. N. Ambraseys and C. P. Melville, *A history of Persian earthquakes*, Cambridge University Press, 1982.