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ATTENUATION OF GROUND MOTION OF EARTHQUAKES WITH LARGE FOCAL DEPTHS

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INTRODUCTION: There are many studies on the attenuation characteristics of earthquake ground motion but few consider events with large focal depths. The Kushiro earthquake on January 15, 1993 (M_{JMA}=7.8, focal depth=103.2 km) has demonstrated the importance of earthquakes with focal depths of about 100 km or more. This paper reports on the regression analysis results of 1540 records from 236 events recorded by the new JMA-87 type accelerometers in 76 stations of the Japan Meteorological Agency (JMA).

DATA: Acceleration records of events from August 1, 1988 to August 30, 1992 are used in this study. In addition, acceleration time histories of recent earthquakes like the January 15 Kushiro-Oki earthquake, Febuary 7, 1993 Noto Peninsula earthquake (M_{JMA}=6.6, focal depth=24.8 km) and the July 12, 1993 Hokkaido Nansei-Oki earthquake (M_{JMA}=7.8, focal depth=34 km) are included. Due to the resolution (± 0.03 cm/s^2) of the recording instrument, only records whose peak ground acceleration (PGA) are greater than or equal to 1.0 cm/s^2 for both horizontal components are used. Events whose focal depth are reported by the JMA as zero and those greater than 200 km are omitted from the analysis. Figure 1 shows the distribution of the JMA magnitude, focal depth and hypocentral distance. It can be seen that there is a positive correlation of the magnitude and hypocentral distance.

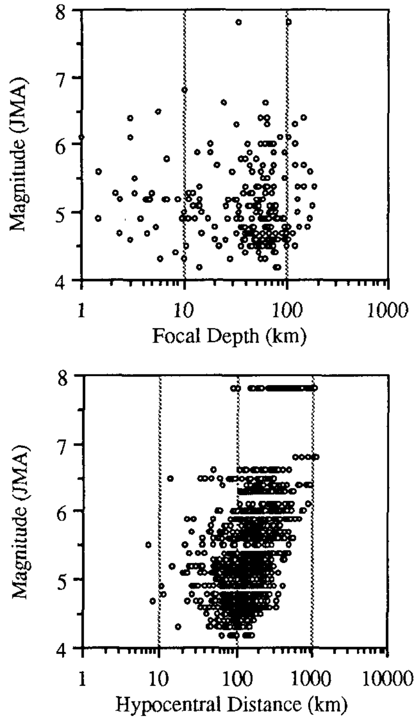

Figure 1. Distribution of magnitude, focal depth and hypocentral distance of data set

ATTENUATION MODEL: The attenuation model considered in this paper is of the form:

$$\log y = b_0 + b_1 M + b_2 R + b_3 \log R + b_4 h + \sum_{i=1}^{N} c_i S_i \qquad (1)$$

where y is the ground motion index under consideration (larger of the two horizontal components), M is the JMA magnitude, R is the hypocentral distance in km, h is the focal depth in km, S_i = 1 for station i, 0 otherwise and b_i's and c_i's are the coefficients to be determined. The inclusion of the focal depth term b_4 and the station correction terms, c_i are justified by the behaviour of residuals if they are not considered and by the significant improvement of the regression fitting.

METHOD OF ANALYSIS: Fukushima and Tanaka [1] have shown that the correlation of the magnitude and distance will result in systematic errors if simple multilinear regression is used. A two-stage regression method similar to Joyner and Boore [2] to separate the distance dependence from the magnitude dependence is therefore desirable. However, since the hypocentral distance is also correlated to the focal depth, the multicollinearity problem is increased. Two-stage regression methods use dummy variables to separate the magnitude dependence. However, since the computation of station corrections also involve the use of dummy variables the resulting matrix of known values is singular. In this study, the problem is solved by using an iterative three-stage approach.

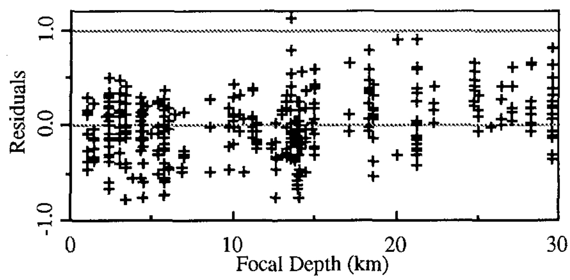

Figure 2. Plot of residuals with respect to focal depth for events with focal depths from 0.1 to 30 km.

The initial step involves the determination of all coefficients in Equation 1 by regression using dummy variables for each station. The second step is the determination of the distance dependent terms from the model

$$\log y = \sum_{j=1}^{K} a_j A_j + b_2 R + b_3 \log R + \underline{b_4} h + \sum_{i=1}^{N} \underline{c_i} S_i \qquad (2)$$

where $A_j = 1$ for earthquake j with magnitude M_j, 0 otherwise and b_4 and c_i's are constrained to the values determined in the previous step. The third step is to determine the magnitude dependence by the equation

$$a_j = b_0 + b_1 M_j \qquad (3)$$

in which a_j is determined from the previous step. The regression is carried out with weighted least squares [3] using the inverse of the variance-covariance matrix from the previous step. The first step is then repeated except that b_1 to b_3 are constrained to the values determined from the previous iteration's step 2 and 3. The cycle is then repeated until the values of the coefficients stabilize.

RESULTS: To determine the effect of the focal depth term and station corrections, regressions were performed with b_4 and c_i's constrained to zero and with the terms unconstrained. To minimize the correlation between hypocentral distance and focal depth, the data set was initially limited for focal depths of 0.1 to 30 km. A plot of the residuals with respect to the focal depth (Figure 2) shows a linear trend. Figure 3 shows the mean and standard deviation of residuals for each station. There is a definite trend of the residuals for each recording station.

The iterative three-stage analysis is then performed for the whole data set. The coefficients stabilized after 10 iterations. However, b_2 failed the t-test with the null hypothesis, H_0: $b_2 = 0$. The analysis is then repeated with b_2 constrained to zero. The results of the regression are given in Table 1. Figure 4 shows the attenuation of PGA for the 1993 Kushiro-Oki earthquake. The line shows the PGA predicted by equation in Table 1, the squares the recorded PGA, and pluses the PGA after adjustment for the station effect. It can be seen the PGA's show a much better fit after the site effect is considered and that the slope of the regression line coincides well with the data.

CONCLUSIONS: A regression analysis of the PGA and PGV recorded from 76 JMA stations using the new JMA-87 type accelerometer is performed. A total of 1540 records from 236 events with focal depths up to 200 km. are used. The effects of the focal depth and local site considered in the analysis. It was found that the focal depth and recording station contribute a significant amount of variability to the PGA and PGV.

Due to the multicollinearity problem an ordinary two-stage regression method is not sufficient. An iterative three-step procedure is introduced to separate the determination of the focal depth effect and the recording station effect and the distance dependence and magnitude dependence. The resulting attenuation equation shows a good fit for the PGA data of the Kushiro-Oki earthquake especially after adjustment for the station effect.

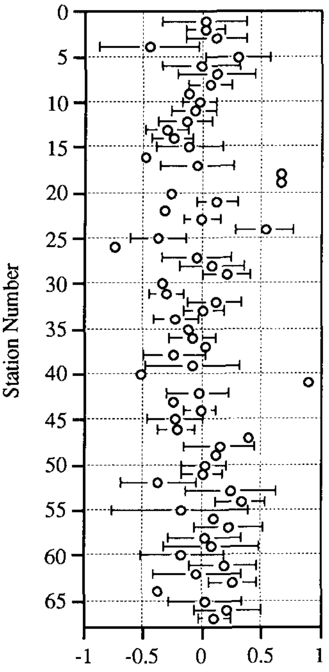

Figure 3. Mean and standard deviation (error bars) of the residuals for each station.

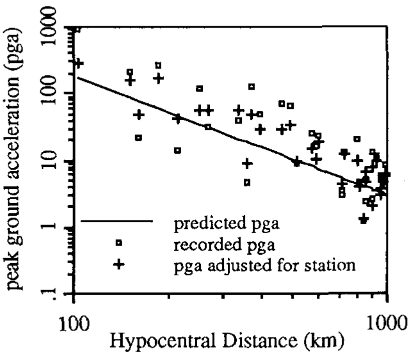

Figure 4. Attenuation of recorded pga and pga adjusted for station effect.

Table 1. Regression constants for log PGA using events with focal depths from 0.1 to 30 km

log y	b_0	b_1	b_2	b_3	b_4
PGA	1.5843	0.4973	<u>0.0</u>	-1.7916	0.00366
PGV	-0.5929	0.6484	<u>0.0</u>	-1.6837	0.00260

References:

[1] Y. Fukushima and T. Tanaka (1991). A new attenuation relationship for peak horizontal acceleration of strong earthquake ground motion in Japan. *Bull. Seis. Soc. Am.* **80:4**, 757-783.
[2] W.B. Joyner and D.M. Boore (1981). Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley, California earthquake. *Bull. Seis. Soc. Am.* **71**, 2011-2038.
[3] N. Draper and H. Smith (1981). *Applied regression analysis (2nd ed.).* John Wiley and sons.