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VARIANCE OF PEAK GROUND ACCELERATION AND VELOCITY IN ATTENUATION RELATIONSHIPS

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SUMMARY

The variance of peak horizontal acceleration and velocity is examined using the Japanese strong-motion data. The empirical attenuation relationships for peak acceleration and velocity are developed from more than three thousand Japanese data. The errors of the data from the attenuation relationships are examined. The standard error decreases with increasing magnitude, with decreasing distance, and with increasing amplitude. The distance dependence is clear at distances shorter than 50km and can be interpreted by local and regional variations of scattering and absorption of seismic waves in the path. The amplitude dependence of the error is much stronger than the magnitude and distance dependences. As the amplitude level is controlled by magnitude and distance, the strong amplitude dependence would be due to the multiple effect of the magnitude and distance dependences.

INTRODUCTION

The empirical attenuation relationships of ground motion have been frequently used in strong motion prediction for seismic design of structures and earthquake damage assessment. Although the attenuation relationships can predict ground motion intensity with small number of the parameters, the scatter of the data from the relationship is large. The standard deviations of the relationships range 0.2 to 0.3 in the common logarithmic scale (Abrahamson [1]). This means the need of revision of the attenuation model for more accurate prediction. The variance of ground motion intensity in the attenuation relationships is also an important key to control the seismic hazard curve at low probability, which affects the design earthquake motion of critical structures.

In the previous studies, the dependence of the variance on ground motion level has been pointed out by Donovan [2] and Campbell [3]. The magnitude dependence has been also pointed out by Campbell [3], Idriss [4] and Youngs [5]. Although some possible interpretations for the dependences have been shown in the studies such as the effects of nonlinear soil response and change of predominant periods with magnitude, the origins of the variability have not been discussed fully.

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This paper examines the variance of peak horizontal acceleration and velocity in the attenuation relationships. The empirical attenuation relationships for peak ground acceleration (PGA) and velocity (PGV) are developed by using more than three thousand strong-motion data from Japanese earthquakes. The characteristics of the errors of the data from the empirical attenuation relationships are discussed in order to examine the origins of the variance.

DATABASE

The data from thirty-three Japanese earthquakes occurred in 1968 to 2001 are compiled in the database as shown in Table 1. The earthquakes are crustal, inter-plate and intra-plate earthquakes. The magnitude and focal depth range 5.5 to 8.3 and 3km to 120km, respectively. In the database, there are 3335 PGA data and 1980 PGV data. All the data are recorded at free field sites or small buildings where soil-structure interaction effects are negligible. As the data are observed with different types of the instrument, the data are instrumentally corrected with the band-pass filter (Si [6]). The peak ground motion is defined as the larger one of the two horizontal components. The closest distance to the fault plane is used as the distance. In Fig. 1, distributions in magnitude and fault distance of the data set for PGA and PGV are illustrated.

To evaluate the site effects on ground motion, we compiled the soil profiles at the observation stations. First, we classified soil characteristics into two categories, rock and soil, for all the observation stations. The definition of rock and soil is after Joyner [7]. For the stations with more details of soil profile, we calculate the average shear wave velocity from surface to a depth of 30m, refer to as AVS30 hereafter, at the site. As the station correction, the PGA values observed on rock sites are multiplied by 1.4 in order to normarize to the values on soil sites. The PGV values are divided by the amplification factor estimated from the AVS30 (Midorikawa [8]) in order to normarize to the values on stiff sites where the AVS30 is about 600m/s.

REGRESSION ANALYSIS

The following regression models are used in the analysis. As the attenuation decay is significantly larger for deeper earthquakes than for shallower earthquakes, the different equations are used for earthquakes deeper than 30km and shallower (Midorikawa [9]);

$$\log A = b - \log (X + c) - k X \quad (D \leqq 30\text{km}) \tag{1}$$
$$\log A = b + 0.6 \log (1.7D + c) - 1.6 \log (X + c) - k X \quad (D > 30\text{km}) \tag{2}$$

where, A is peak ground motion, and X and D are fault distance and focal depth in km. The first term in Eq. (1), i.e., the coefficient b is an offset factor for each earthquake. The second term shows geometrical attenuation, and the third term shows anelastic attenuation. For the coefficient k, we fix at 0.003 for PGA and 0.002 for PGV (Si [6]). The coefficient c is introduced accounting for the saturation of the amplitude of strong motion in the near-source area, and is given as a function of magnitude (Si [6]);

$$c = 0.0060\ 10^{0.5M_w} \quad \text{(for PGA)} \tag{3}$$
$$c = 0.0028\ 10^{0.5M_w} \quad \text{(for PGV)} \tag{4}$$

where M_w is moment magnitude.

For b, the focal depth and the fault type, such as crustal, inter-plate and intra-plate types, are considered in the regression model (Si [6]);

$$b = a\,M_w + h\,D + d_i\,S_i + e \qquad (5)$$

where, S_i is dummy variable for fault type i, and a, h, d_i and e are the regression coefficients. The coefficients and standard deviations obtained by the regression analysis are shown in Table 2. Figure 2 shows the attenuation curves from the regression model. The upper part shows the curves for M7 intra-plate earthquakes with different focal depth. The lower part shows the curves for M7 shallow earthquakes with different fault type.

CHARACTERISTICS OF VARIANCE IN ATTENUATION RELATIONSHIPS

The deviation of the data from the attenuation relationships is shown in Fig. 3. The figure shows the ratio of the data to the predicted value in the common logarithmic scale. The ratio is called the total error. In this study, the common logarithmic scale is used. The figure shows that the error is lognormally distributed. The standard deviations are 0.30 for PGA and 0.28 for PGV. The total error can be separated into the inter-event and intra-event errors (Youngs [5]). In Table 2, the standard deviations of the intra-event, inter-event and total errors are shown. The intra-event error is substantially larger than the inter-event error, as has been pointed out by the previous studies (Campbell [3], Youngs [5]).

Figure 4 shows the magnitude dependence of the errors. The upper part of the figure shows the errors of the individual data, and the lower part shows the standard deviation in four magnitude ranges, 5.5 to 5.9, 6.0 to 6.5, 6.6 to 6.9, and 7.6 to 8.3. In the figure, the relationships proposed by the previous studies (Youngs [5], Youngs [10], Campbell [11]) are also shown. The error decreases slightly with increase of magnitude, but no strong dependence is observed. Figure 5 shows the distance dependence of the errors. At the distance range over 50km, the errors are almost constant, but slightly increase with increase of distance. At the shorter distance, the errors decrease clearly with decrease of distance. The standard deviations are about 0.3 at distance of 50km and about 0.2 at distance of 10km.

Figure 6 shows the amplitude dependence of the errors. The errors decrease clearly with increase of amplitude. The standard deviations are 0.32 for PGA smaller than 50cm/s^2 and 0.14 for PGA larger than 600cm/s^2. The standard deviation for all the PGA is 0.30 as has been mentioned. This value seems to be controlled by the smaller amplitude data which account for a majority of the dataset used. For PGV, the results are almost the same.

To summarize the results, the error decreases with increasing magnitude, with decreasing distance, and with increasing amplitude. The magnitude dependence of the error is not strong. The distance dependence is clear at distances shorter than 50km. The amplitude dependence is much stronger than the magnitude and distance dependences. The standard deviations are about 0.15 at larger amplitude level and about 0.3 at smaller amplitude level. As the amplitude level is controlled by magnitude and distance, the strong amplitude dependence would be due to the multiple effect of the magnitude and distance dependences.

DISCUSSIONS

The origins of the variance of the data from the attenuation relationship come from the source, path and site effects. The plausible causes from the sources effects are that (a) magnitude may not be an adequate scale to evaluate the amplitude of the seismic waves generated from the source and (b) the radiation pattern and source directivity may affect the variance of the amplitude. Regarding (a), Youngs [5] suggested that the magnitude dependence of the error may be caused by magnitude-dependent variability of the stress drop. This seems acceptable as a possible interpretation of the magnitude dependence of the error mentioned before. Regarding (b), the effects of the radiation pattern are not significant at short periods (Satoh [12]). The directivity effects are significant only at shorter distances (Somerville [13]). The effects do not seem significant and may not be main causes of the errors.

The plausible cause from the path effects is (c) variety of attenuation of the seismic waves due to randomness in the propagation path. Hoshiba [14] shows large variability of the amplitude at distance of several tens km due to small local randomness of the velocity structure of the propagation path by the numerical simulation. Nakamura [15] shows large regional variation of the Q-structure in Japan. These results suggest that the errors from local and regional variations of scattering and absorption of seismic waves in the path can be large and that the path effects can interpret the distance dependence.

The plausible cause from the site effects is (d) variety of local site amplifications on the data. From the analysis of the dense strong-motion array data (Midorikawa [16]), the error due to the site effects is roughly estimated about 0.15. This suggests that the site effects may not be a dominant factor in the total error, which is consistent with the results by Lee [17]. In connection with the site effects, nonlinear soil response has been used as an interpretation of the amplitude dependence of the error (Donovan [2]). Figure 7 shows the plots of distance and PGA or PGV for all the data used. For PGA, the values tend to saturate at several hundred cm/s^2, which may suggest the effects of nonlinear soil response. For PGV, however, the tendency of the saturation is not observed. Figure 8 shows the amplitude dependence of the errors for different soil categories. In the figure, the average shear-wave velocity of upper 30m is used as the soil category. Although the dependence of PGA shown in the upper part of the figure is smaller for stiff ground than for soft ground, the dependence of PGV shown in the lower part seems almost same for soft and stiff grounds. This suggests that nonlinear soil response which should be significant on softer ground would not be a main cause of the amplitude dependence at least for PGV.

From the discussions mentioned above, it is not easy to identify main causes of the variance. As the inter-event error is significantly smaller than the intra-event error, the source effects which will affect to the inter-event error rather than the intra-event error may not be the main cause. Then, the path and site effects may be candidates for the main cause. The previous studies (Midorikawa [16], Lee [17]) suggest that the variance can not be interpreted by the site effects alone. Regarding the path effects, it is very difficult to evaluate them quantitatively. The path effects, however, seem to play an important role to control the variance, since the error decreases clearly at shorter distances.

CONCLUSIONS

The variance of peak horizontal acceleration and velocity in the attenuation relationships is examined. The empirical attenuation relationships for peak ground acceleration and velocity are developed by using more than three thousand strong-motion data from thirty-three Japanese earthquakes with magnitude of 5.5 to 8.3. The errors of the data from the empirical attenuation relationships are examined. The standard error decreases with increasing magnitude, with decreasing the distance, and with increasing the amplitude. The magnitude dependence of the error is not strong. The distance dependence is clear at distances shorter than 50km and can be interpreted by local and regional variations of scattering and absorption of seismic waves in the path. The amplitude dependence of the error is much stronger than the magnitude and distance dependences. The standard error in the common logarithmic scale is about 0.15 at larger amplitude level and about 0.3 at smaller amplitude level. As the amplitude level is controlled by magnitude and distance, the strong amplitude dependence would be due to the multiple effect of the magnitude and distance dependences.

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Table 1 List of data used

No.	Earthquake	Date	Mw	Focal Depth (km)	Number of recordings		Fault Type
					P.G.A.	P.G.V.	
1	Off Tokachi	1968.5.16	8.2	15	10	10	Inter-plate
2	Off Nemuro Pen.	1973.6.17	7.8	25	5	4	Inter-plate
3	Near Izu Oshima	1978.1.14	6.6	7	8	8	Crustal
4	Off Miyagi Pref.	1978.6.12	7.6	37	13	10	Inter-plate
5	East off Izu Pen.	1980.6.29	6.5	7	15	15	Crustal
6	Off Urakawa	1982.3.21	6.9	25	10	8	Crustal
7	Nihonkai-Chubu	1983.5.26	7.8	6	17	17	Inter-plate
8	Off Hyuganada	1984.8.7	6.9	30	9	7	Intra-plate
9	Central Iwate Pref.	1987.1.9	6.6	73	9	5	Intra-plate
10	Northern Hidaka Mt.	1987.1.14	6.8	120	13	6	Intra-plate
11	East off Chiba Pref.	1987.12.17	6.7	30	173	47	Crustal
12	Off Kushiro	1993.1.15	7.6	105	35	17	Intra-plate
13	Off Noto Pen.	1993.2.7	6.3	15	12	7	Crustal
14	Southwest off Hokkaido	1993.7.12	7.7	10	24	15	Inter-plate
15	East off Hokkaido	1994.10.4	8.3	35	41	17	Intra-plate
16	Far off Sanriku	1994.12.28	7.7	35	57	21	Inter-plate
17	Hyogo-ken Nanbu	1995.1.17	6.9	10	74	43	Crustal
18	Off Hyuganada	1996.10.19	6.7	25	159	98	Inter-plate
19	Northwestern Kagoshima Pref.	1997.3.26	6.1	6	121	65	Crustal
20	Northwestern Kagoshima Pref.	1997.5.13	6.0	7	133	71	Crustal
21	Northern Yamaguchi Pref.	1997.6.25	5.8	10	196	82	Crustal
22	Off Shizuoka Pref.	1998.5.3	5.5	3	77	46	Crustal
23	Northern Iwate Pref.	1998.9.3	5.8	10	66	26	Crustal
24	Off Hyuganada	1998.12.16	5.8	32	44	30	Inter-plate
25	Southeastern Hokkaido	1999.5.13	6.4	104	96	45	Intra-plate
26	Northern Wakayama Pref.	1999.8.21	5.8	70	249	172	Intra-plate
27	Off Nemuro Pen.	2000.1.28	6.7	56	46	21	Intra-plate
28	Northeastern Chiba Pref.	2000.6.3	5.9	48	135	90	Inter-plate
29	Off Ibaraki Pref.	2000.7.21	6.1	49	176	108	Inter-plate
30	Tottori-ken Seibu	2000.10.6	6.8	11	370	207	Crustal
31	Central Mie Pref.	2000.10.31	5.5	43	278	198	Intra-plate
32	Geiyo	2001.3.24	6.7	51	411	263	Intra-plate
33	Off Hyuganada	2001.4.25	5.6	42	253	201	Intra-plate

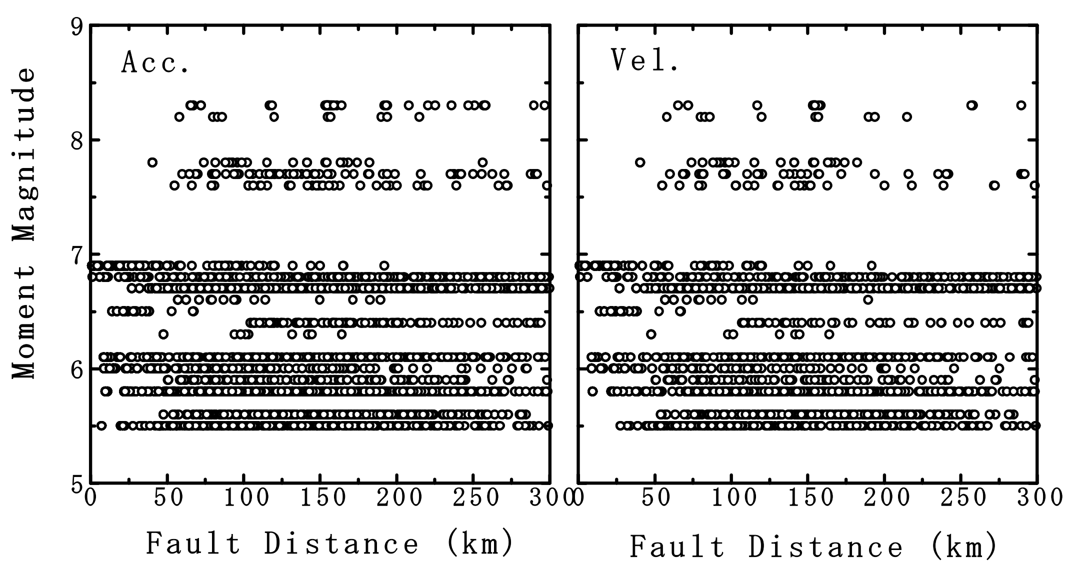
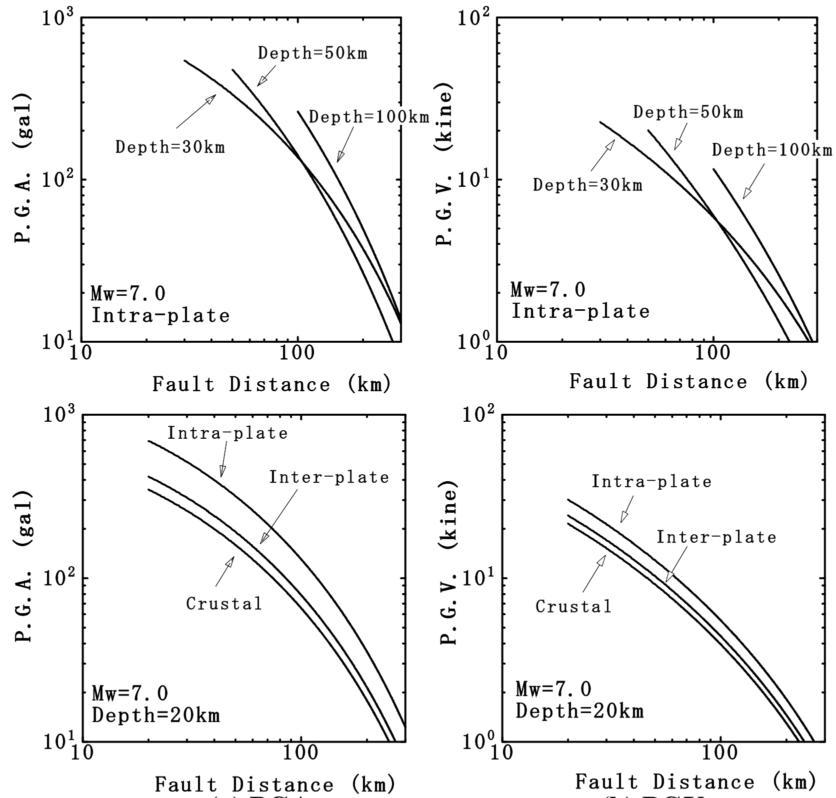


Fig. 1 Distance vs. M_w

Table 2 Coefficients from regression analysis

a	h	d			e	Intra-event Standard deviation	Inter-event Standard deviation	Total Standard deviation
		Crustal	Inter-plate	Intra-plate				
Peak ground acceleration								
0.59	0.0023	0.00	0.08	0.30	0.02	0.27	0.16	0.30
Peak ground velocity								
0.65	0.0024	0.00	0.05	0.15	-1.77	0.24	0.16	0.28



(a) PGA **(b) PGV**

Fig. 2 Attenuation curves from regression analysis

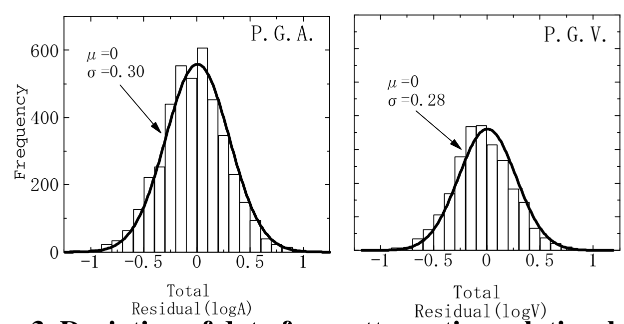
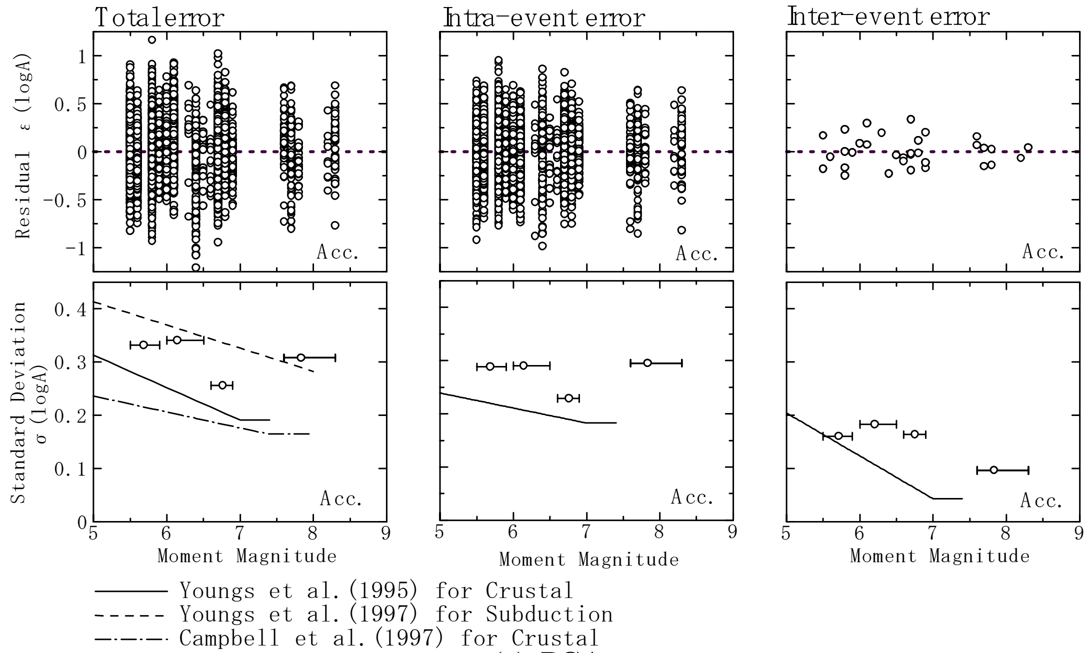
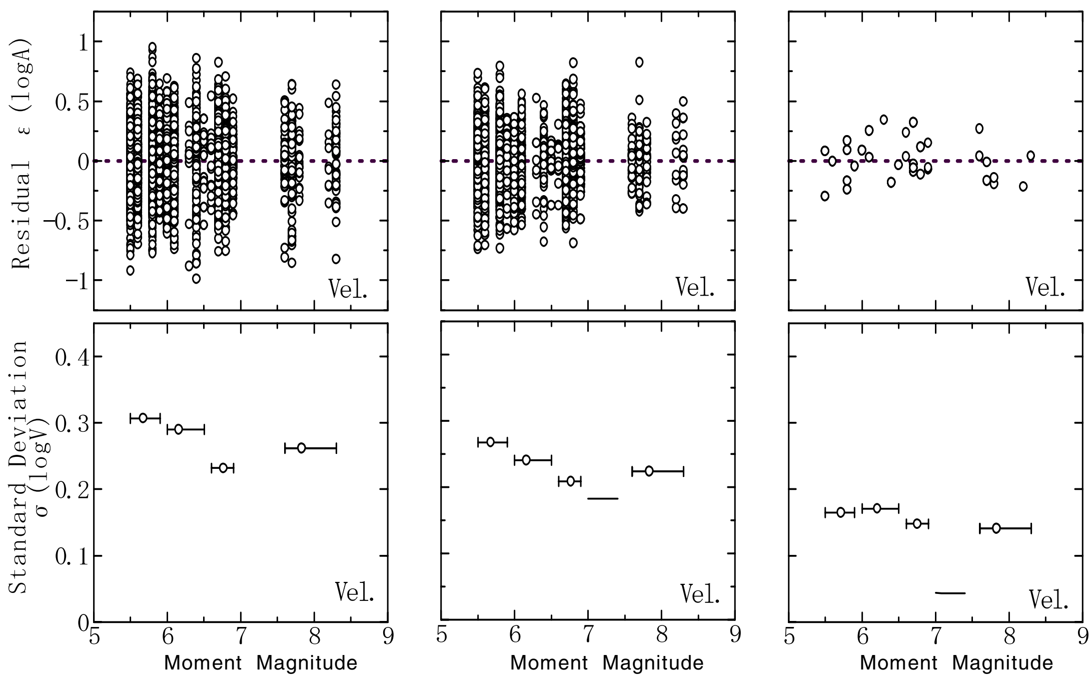


Fig. 3 Deviation of data from attenuation relationships



(a) PGA



(b) PGV

Fig. 4 Magnitude vs. Deviation

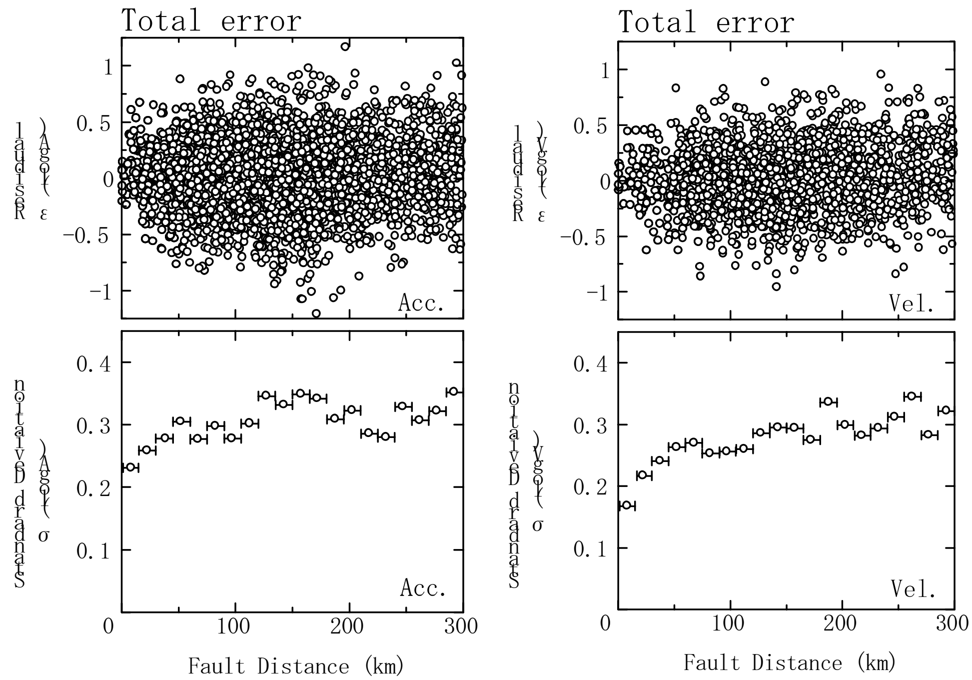


Fig. 5 Distance vs. Deviation

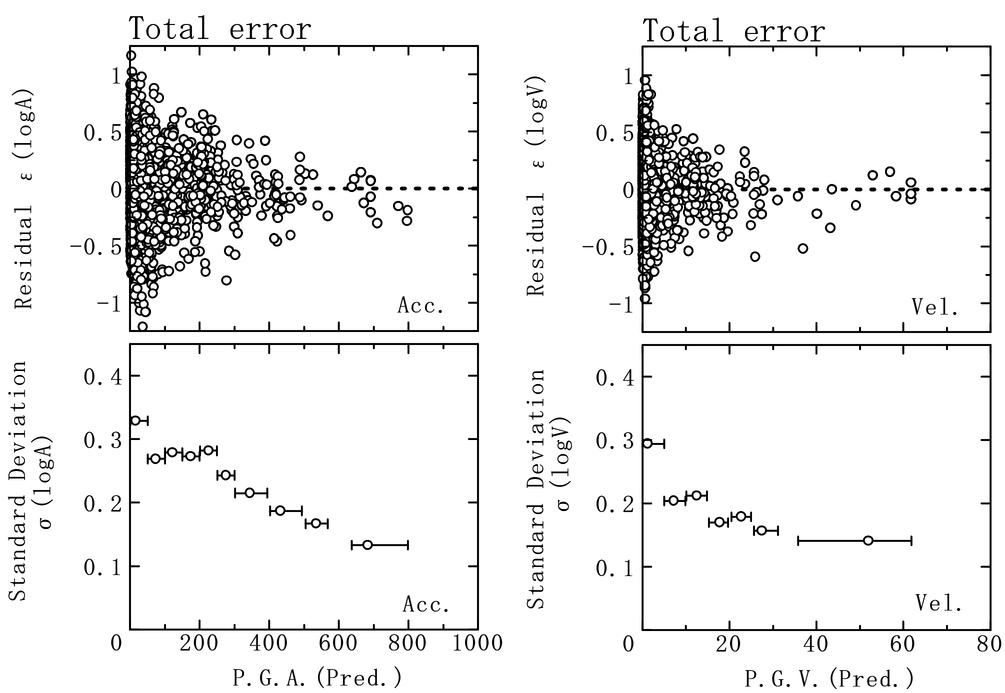
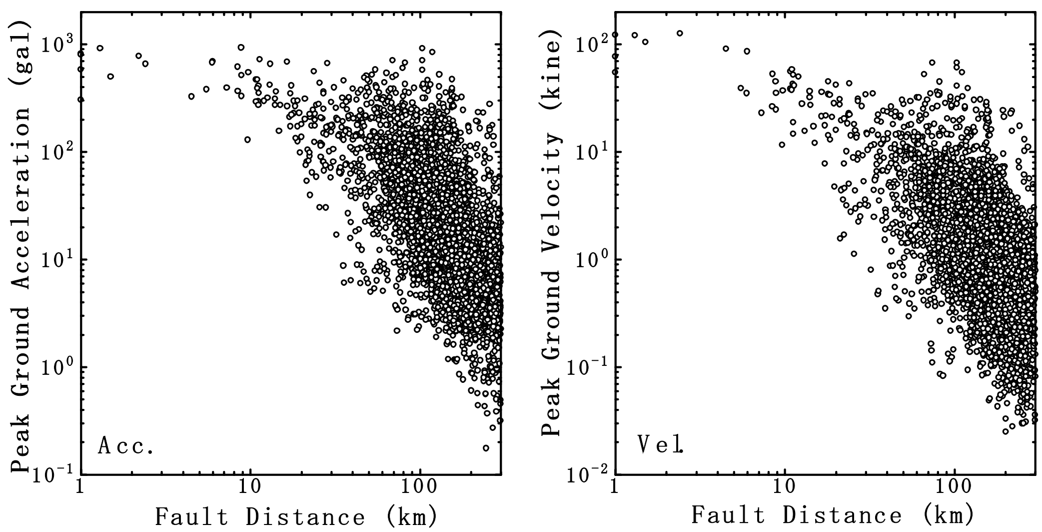


Fig. 6 Amplitude vs. Deviation



(a) PGA **(b) PGV**

Fig. 7 Distance vs. PGA or PGV used

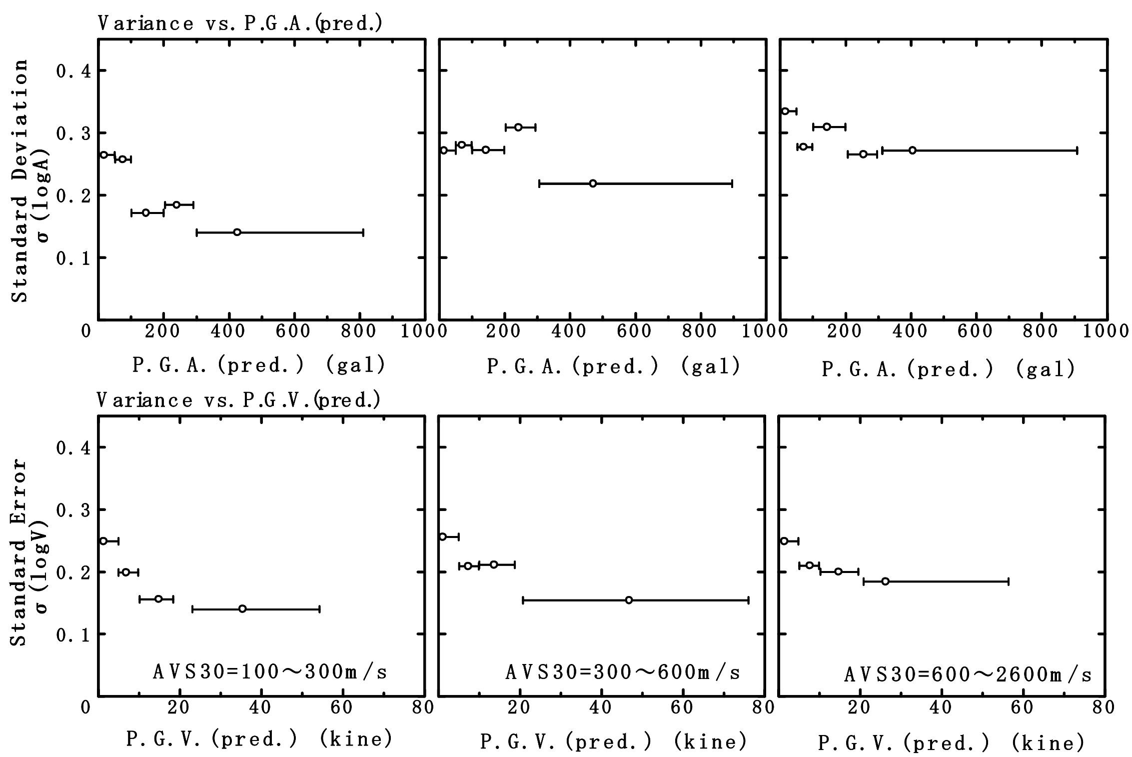


Fig. 8 Deviation vs. Amplitude with different soil category