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EVALUATION OF HANGING WALL EFFECTS ON GROUND MOTION ATTENUATION RELATIONSHIP CORRECTING THE SITE EFFECTS

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ABSTRACT

In this study, firstly we present a simple method to correct for site effects. In this method, the site effect correction factor for an observation station is defined as the residual between the observed strong motion and the prediction by a reference attenuation model defined on bedrock. Consequently, if a station always shows stronger or weaker motion it will be corrected to show an average one on bedrock. Using the corrected strong motion records then we can analyze the hanging wall effects with relatively smaller influence of site condition. The method is applied to the 1994 Northridge earthquake which the hanging wall effects have been indicated. The results indicated that, generally the hanging wall effects derived in this study is almost consistent with the results in the past study.

Introduction

Several authors have indicated that the strong motions on the hanging wall are greater than on the foot wall of dipping fault, referred to as hanging wall effects, such as Abrahamson and Somerville (1996) for the 1994 Northridge earthquake, Chang et al. (2004) for the 1999 Chichi earthquake, and Si and Midorikawa (2005) for the 2004 Mid-Niigata prefecture earthquake. The hanging wall effects have also been considered in some of the NGA attenuation models, such as Abrahamson and Silva (2008), Campbell and Bozorgnia (2008). Despite these previous works, however, there is still a question of whether these site effects have been corrected properly.

In this study, we present a simple method to correct for site effects. In this method, the site effect correction factor for an observation station is defined as the residual between the observational strong motions with that predicted by a reference attenuation model defined on bedrock. Consequently, if a station always shows stronger or weaker motion it will be corrected to show average ones on bedrock. This method is useful for peak ground velocity and longer period components, but may be not enough for peak ground acceleration and shorter period components because of the possible nonlinear behavior. For the latter case, the effect of the nonlinear behavior should be examined when using the method proposed in this study, and if necessary the correction for nonlinear behavior should be performed.

Using the corrected strong motion records we can analyze the hanging wall effects with

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relatively smaller influence of site condition. The method is applied to the 1994 Northridge earthquake which the hanging wall effects have been indicated, and the hanging wall effects for the earthquake are evaluated.

Methodology

Evaluation of site effect

Generally, the observation of strong motion O(ω) can be represented by the convolution of the seismic source S(ω), path P(ω), and the site effect G(ω), as shown in Eq.1.

$$O(\omega)=S(\omega)*P(\omega)*G(\omega) \quad (1)$$

where, ω is frequency. Among these factors, the site effect G(ω) has great influence on strong motion and is difficult to estimate in an attenuation relation. Here, we propose a new simple method to estimate the site effect and apply it to evaluate the hanging wall effect.

The strong motion predicted by an attenuation model can be written as Eq.2.

$$O'(\omega)=S'(\omega)*P'(\omega)*G'(\omega) \quad (2)$$

where, O' is a parameter of strong motion, such as PGA or PGV, S'(ω), P'(ω) are source and path term defined by an attenuation model, respectively. G'(ω) is the site effect from seismic bedrock to the bedrock where the attenuation model defined on. Here, we call this attenuation model the reference attenuation model. Assuming the terms seismic source and the path effect can be represented by the reference attenuation model, we get S'(ω)=S(ω), and P'(ω)=P(ω). So the site effects respect to bedrock the reference attenuation model defined on can be written as Eq.3.

$$O(\omega)/O'(\omega)=G(\omega)/G'(\omega)+\varepsilon \quad (3)$$

where, ε shows the possible biases come from the source, path effects and the influence from deep substructure, which are expected to be a random number. In fact, ε for a specific strong motion record at an observation station during an earthquake shows a bias, sometime significant bias. For eliminating the bias, we perform an average operation using a number of records at the observation station, as shown in Eq. 4.

$$R(\omega)=\frac{1}{n}\sum_{i=1}^{n}\left(\frac{G_i(\omega)}{G'(\omega)}+\varepsilon_i\right) \quad (4)$$

where, i is a specific record from an earthquake, *n* is the total number of the records used in estimation of the site effects. In this case, since ε_i is a random number, so the larger n becomes, the smaller the term $\Sigma\varepsilon_i /n$ will be. This means that *R(ω)* can represent the site effects if there are sufficient records in the analysis. Here, we define such *R(ω)* as the site effect correction factor, which to be used to correct the site effect as follows.

$$O_r(\omega) = O_s(\omega)/R(\omega) \quad (5)$$

where, $O_s(\omega)$ is the original observation strong motion, and $O_r(\omega)$ is that corrected on bedrock.

Evaluation of hanging wall effect

In this study, the hanging wall effects are analyzed in the following steps: (1) correction of the site effect for data recorded during the target earthquake; (2) calculation of the residual between the observed strong motion and that predicted by a reference attenuation model; (3) modification of the rupture directivity effects if applicable; (4) evaluation of the hanging wall effects based on the analysis of residuals between the observation and the reference model.

Data

In this study, the records derived during the 1994 Northridge earthquake will be used in the analysis. The peak horizontal ground velocity (refer to as PGV hereafter) is adopted as the strong motion parameter since the nonlinear effects can be neglected, and its value on bedrock can be defined by an existing attenuation model developed by Si and Midorikawa (1999), which will be introduced later.

All the PGV data used in the analysis are selected from the database provided by the NGA project (Chiou et al., 2008). In the database, all the earthquakes are checked if the observation stations have two or more records in which the recording of the 1994 Northridge earthquake must be included. The earthquakes with such observation stations are listed in Table 1.

In order to avoid the complexity of the source characteristics, we eliminated the data located in the hanging wall area except the data from Northridge earthquake. In order to reduce the effects of path, the data used in this study are limited to a fault distance of 50 km. The earthquakes with EQID of 0145 and 0147 are also eliminated from the database because the data number is small and the discrepancies with the reference model are large. The records at Pacoima dam (left abutment) is also eliminated from the database since the records are thought to be affected by topography.

Analysis

The reference attenuation model

The attenuation relationship proposed by Si and Midorikawa (1999, 2000, refer to as SM99 model hereafter) mentioned above was developed based on the database derived in Japan, including earthquakes with a range of moment magnitudes covered from 5.8 to 8.3. In their models, PGV is defined on bedrock with a shear wave velocity of about 600 m/s. The earthquakes are classified into three types, that is, crustal, inter-plate and intra-plate earthquakes. SM99 models are shown in Eq.6 as follows.

$$\log PGV = 0.58\,M_w + 0.0038D + d - \log(X + 0.0028 \cdot 10^{0.5\,Mw}) - 0.002\,X - 1.29 \quad (6)$$

where X, M_w show fault distance, and moment magnitude, respectively. D is focal depth represented by the depth of the center of a fault plane. *d* shows the coefficient for earthquake types: 0.0 for crustal, -0.02 and 0.12 for inter- and intra-plate events, respectively.

This model has been checked by many earthquakes occurred in Japan with different earthquake types after the attenuation model was published. The model is also checked by the strong motion recorded during the M8.0 Wenchuan, 2008 China earthquake, implicated that it is applicable to M8 class crustal earthquake (Si et al., 2008).

In order to check the applicability of SM99 model to the events occurred in North America, we compared the PGA and PGV derived during the earthquakes listed in Table 1 with the prediction by SM99 model. Part of the results is shown in Fig.1. The data used in the analysis are selected from the database provided by the NGA project, and the PGVs are modified to bedrock with a shear wave velocity about 600 m/s based on the method proposed by Midorikawa et al. (1994). From the comparison, we concluded that the SM99 model fitting the data well, implicating that the model evaluates the source, path effects well for earthquakes occurred in North America.

Attenuation characteristics of peak motion during the 1994 Northridge earthquake

Fig. 2 shows the comparison of peak ground motion recorded during the 1994 Northridge earthquake with the SM99 reference model and the range of 1σ. Here, PGAs are on ground surface and PGVs are corrected to bedrock with a shear wave velocity about 600 m/s. From the figure, we can see the data and the model are well fitted. In the near source area, there are records stronger than the standard reference model, such as record at Tarzana for PGA, and some records with a fault distance less than 10 km for PGV. In order to check the spatial distribution of the PGV, we plotted the residual between the observation and the reference model in the map shown in Fig.3. From the figures, the following can be confirmed: (1) the residuals are larger in the source area, and also in the basin area; (2) the residuals for the corrected PGV on the bedrock are smaller than those calculated from the original records. The results revealed that the possible influence caused by the hanging wall effects and the basin effects. And, of course, also the site effect is also included in the records. For evaluating the hanging wall effect, we firstly evaluate the site effect using the method proposed in the study, and then evaluate the hanging wall without the site effects.

Evaluation of the site effect

From the earthquakes listed in Table 1, the data at the stations located less that 50 km from the fault and with 3 or more records beside the record from the 1994 Northridge earthquake are used in the analysis. All the data satisfied the above criteria are listed in Table 2. The site correction factor $R(\omega)$ are also calculated based on Eq.4 and listed in the table 2, in the column named residuals.

The site effect correction factors derived in the analysis are shown in Fig.4, showing correlation with AVS30. In the figure, the results derived by Fujimoto and Midorikawa (2006) are also plotted in the figure. In the figure, despite some discrepancies, the results derived in this study are almost consistent with the results by Fujimoto and Midorikawa (2006). In Fig.5, the comparison of corrected PGV and the SM99 reference model is plotted. The results show that the corrected PGV is also consistent with the reference model.

Although the number of data used in this study is limited, we can conclude that the method proposed in this study is adequate in evaluating the site effects.

Evaluation of the hanging wall effect

For the evaluation of the hanging wall effect, the residual between the corrected PGV on bedrock and the SM99 reference model are calculated. Fig.6 shows the spatial distribution of the residuals calculated for the observation stations, among them 3 stations located in the hanging wall area, while 1 station located in the foot wall area, and 3 stations located in neither the HW area nor the FW area. The HW and FW stations are listed in Table 2. Different from the NGA database, the Tarzana-Cedar Hill A station is assigned to a HW station. In table 2, besides the parameters of fault distance and the residuals, the rupture directivity factor calculated for HW and FW stations based on Somerville et al. (1997) and the parameters in the NGA database are also shown in Table 2. Since the FW station ELZL, and the HW station JSFP, JSFG are also located in the rupture direction, the residuals are subtracted by the rupture directivity factor. Fig.7 shows the final residuals of PGV on HW and FW stations where the site effects and rupture directivity effects are corrected. In the figure, the result derived by Abrahamson and Somerville (1996) is also plotted. The results derived in this study are consistent with theirs.

Conclusions

In this study, firstly we present a simple method to correct for site effects. In this method, the site effect correction factor for an observation station is defined as the residual between the observed strong motion and the prediction by a reference attenuation model defined on bedrock. Consequently, if a station always shows stronger or weaker motion it will be corrected to show an average one on bedrock. This method is useful for peak ground velocity and longer period components, but may be not enough for peak ground acceleration and shorter period components because of the possible nonlinear behavior. For the latter case, the effects of the nonlinear effects should be examined when using the method proposed in this study, and if necessary a correction should be performed. Using the corrected strong motion records the hanging wall effects can be analyzed with relatively smaller influence of site condition. The method was applied to the 1994 Northridge earthquake which the hanging wall effects have been indicated. The results indicated that, generally the hanging wall effects derived in this study is almost consistent with the results in the past study. However, since there are no sufficient records for the analysis, we will check the method proposed in this study with much more data.

Acknowledgments

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Table 1 List of the earthquakes used in the analysis

EQID	Earthquake Name	YEAR	MODY	Mo (dyne.cm)	Mw
0012	Kern County	1952	0721	1.2303E+27	7.36
0028	Borrego Mtn	1968	0409	9.8855E+25	6.63
0029	Lytle Creek	1970	0912	1.1092E+24	5.33
0030	San Fernando	1971	0209	9.2257E+25	6.61
0101	N. Palm Springs	1986	0708	1.3804E+25	6.06
0113	Whittier Narrows-01	1987	1001	1.0839E+25	5.99
0125	Landers	1992	0628	9.3325E+26	7.28
0126	Big Bear-01	1992	0628	5.4954E+25	6.46
0127	Northridge-01	1994	0117	1.2162E+26	6.69
0145	Sierra Madre	1991	0628	2.9174E+24	5.61
0147	Northridge-02	1994	0117	1.3335E+25	6.05
0148	Northridge-03	1994	0117	7.0795E+23	5.20
0149	Northridge-04	1994	0117	8.8105E+24	5.93
0150	Northridge-05	1994	0117	5.5590E+23	5.13
0151	Northridge-06	1994	0320	9.3325E+23	5.28
0158	Hector Mine	1999	1016	5.5590E+26	7.13
0161	Big Bear-02	2001	0210	6.9984E+22	4.53
0163	Anza-02	2001	1031	2.6915E+23	4.92
0170	Big Bear City	2003	0222	2.6915E+23	4.92

Table 2 data used in the analysis

Site ID No.	Site ID	Site Name	ClstD (km)	FW/HW Indicator	AVS30	Residual to SM99	Rupture Directivity factor
24278	CAST	Castaic - Old Ridge Route	20.72	nu	450.3	0.28	-
24575	ELZL	Elizabeth Lake	36.55	fw	234.9	0.16	0.03
655	JSFP	Jensen Filter Plant	5.43	hw	373.1	0.09	0.04
655	JSFG	Jensen Filter Plant Generator	5.43	hw	525.8	0.08	0.04
24303	LAHW	LA-Hollywood Stor FF	24.03	nu	316.5	0.02	-
24088	PCKC	Pacoima Kagel Canyon	7.26	nu	508.1	-0.17	-
24436	TZCH	Tarzana-Cedar Hill A	15.60	hw	257.2	0.21	-

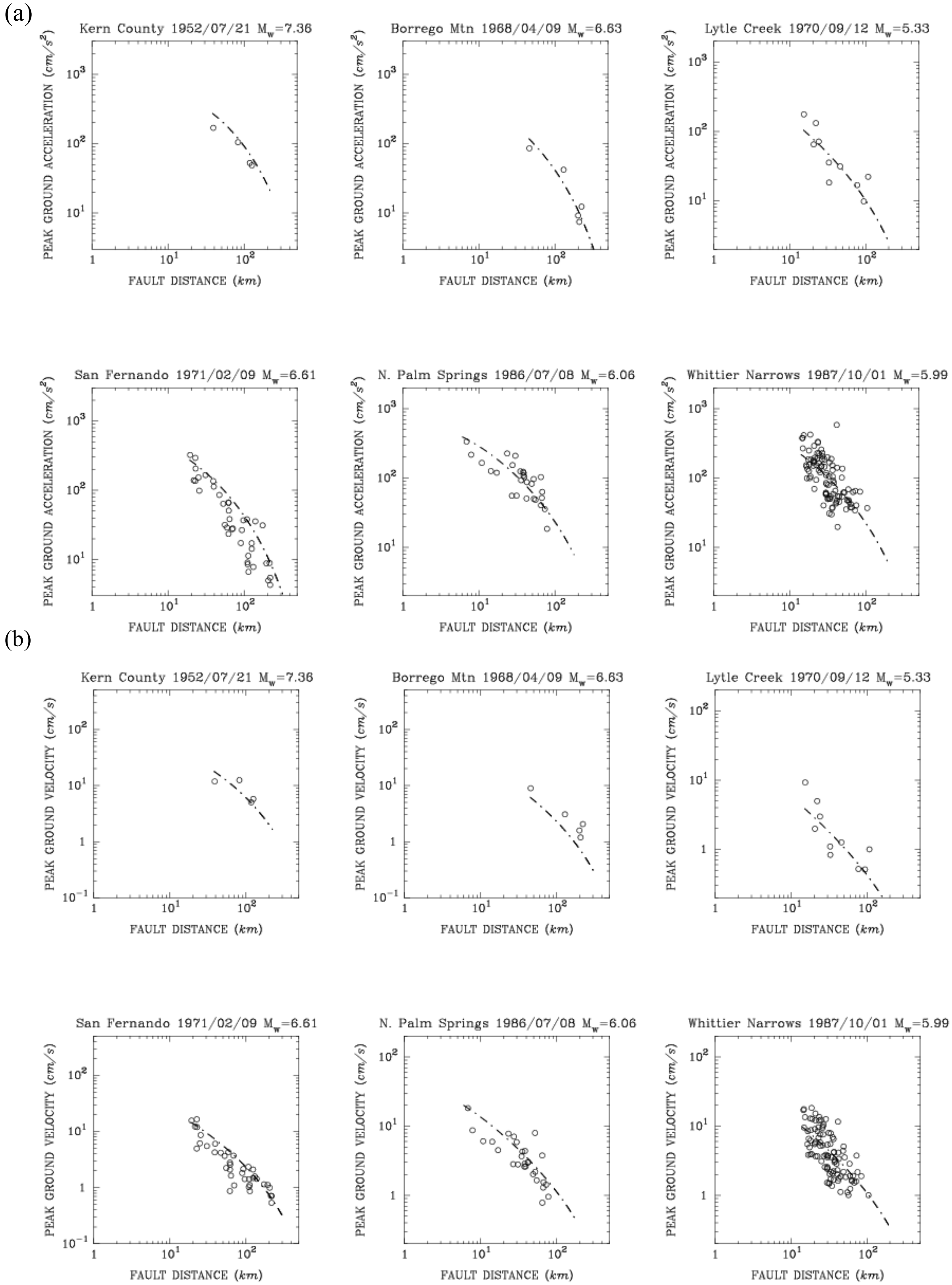

Fig. 1 Comparison of the observation records and the reference attenuation model.
(Top panels (a): PGA, Bottom panels (b): PGV)

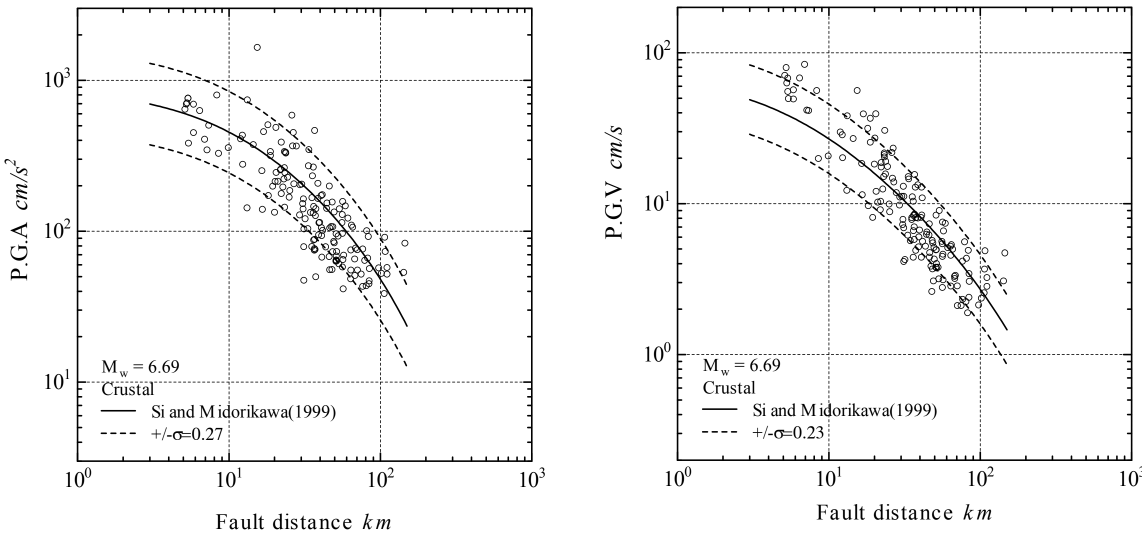

Fig. 2 Attenuation characteristics of peak values for the 1994 Northridge earthquake and the prediction by reference model proposed by Si and Midorikawa (1999) (Left: PGA, right: PGV)

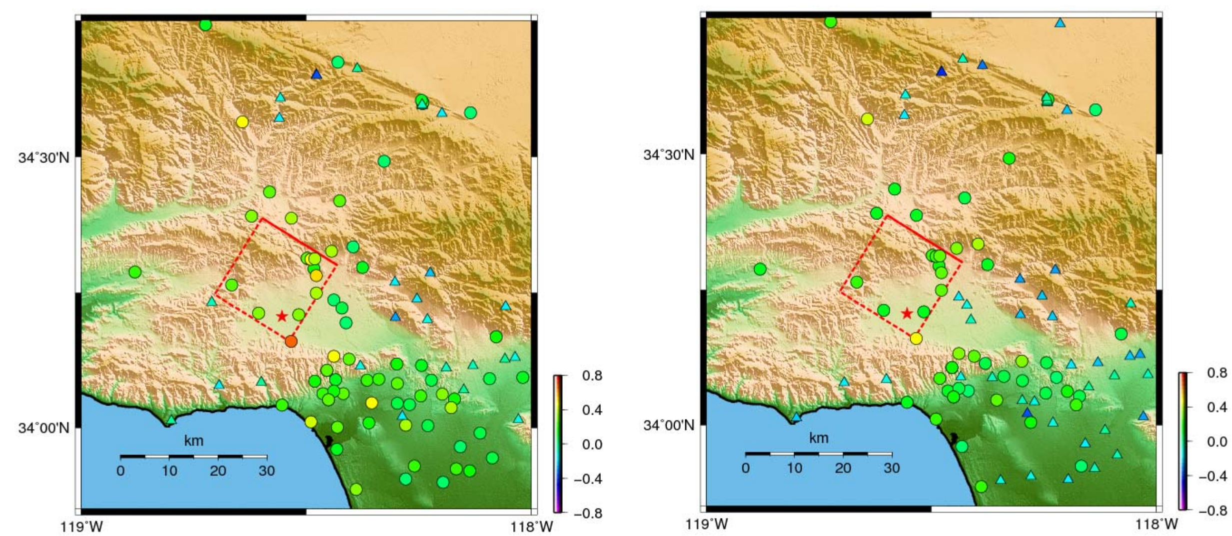

Fig. 3 Distribution of residual between the observations and the results evaluated in study. The left panel shows original observed PGV, the right panel shows PGV corrected to bedrock with Vs 600 m/s. The star shows epicenter. The rectangular shows the projection of the fault plane, and the solid line shows top of the fault, while the broken line shows the dipping parts of the fault. The circle, indicating positive value, shows the observation at a station is larger than the prediction, and a triangle shows the reverse. The size of the circles and the triangles shows the value of the residual at the station.

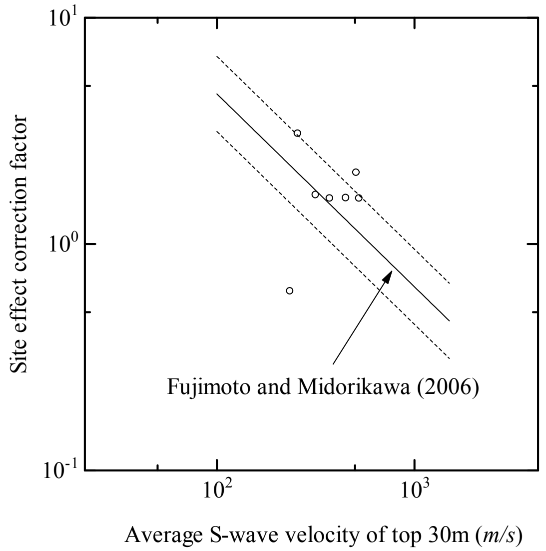

Fig. 4 Comparison of the site effect correction factor and the average S-wave velocity of top 30m

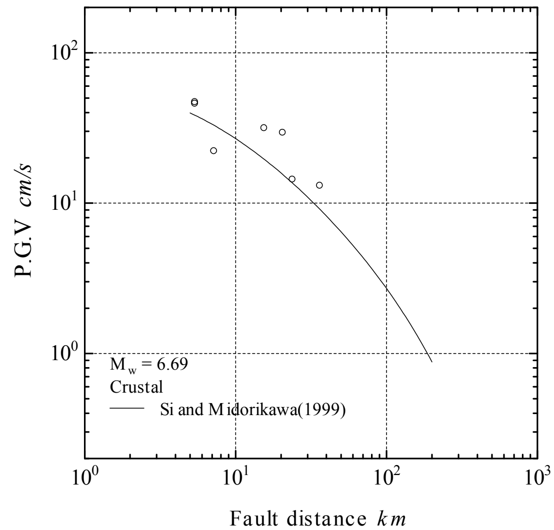

Fig.5 Comparison of the corrected PGV and the reference SM99 model

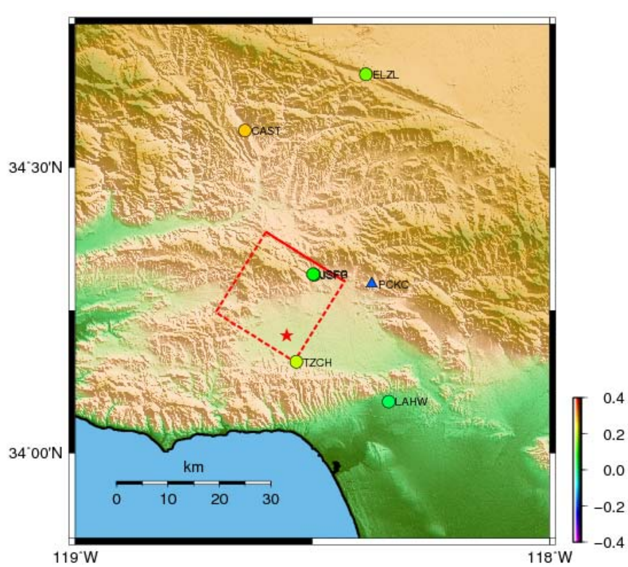

Fig. 6 Distribution of residuals of PGV on bedrock and the reference SM99 model. The symbols are the same as in Fig.3.

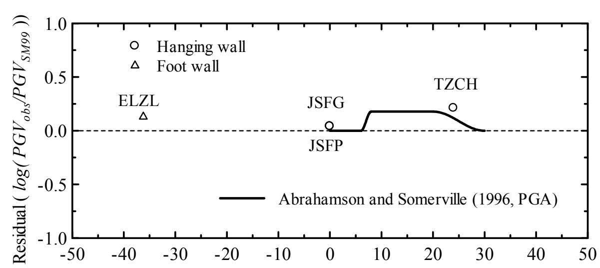

Fig.7 Residual of PGV on HW and FW stations where the site effects are corrected using the method proposed in this study