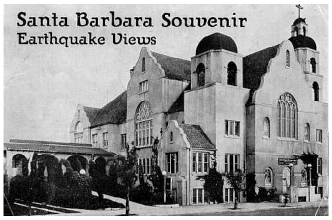

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ESTIMATION OF SITE EFFECTS BASED ON RECORDED DATA AND THE GROUND MOTION ATTENUATION RELATIONSHIP

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ABSTRACT

We investigated a simple method to estimate the site effects on strong ground motion. In this method, the site effect is represented by the mean of the summation of the ratio of observed ground motion over the prediction by a reference ground motion attenuation model. In this study, we analyzed the site effects on peak ground velocity for four regions in Japan. The four regions are the Kanto, Kinki, Chuetsu, and Tottori and Chugoku areas. For each region, we selected strong motion data under the following criteria: (1) earthquakes with an M_{JMA} over 4.0; (2) records with an hypocentral distance less than 100 km and a PGA exceeding 10 cm/s^2; (3) the events for which the attenuation characteristics are generally consistent with the reference ground motion attenuation model, meaning that the source and path effect can be represented by the reference ground motion attenuation model. We checked the results by comparing the correlation between the site effects and the Vs30 derived in this study with the past studies, and found that the results are generally consistent, implicating that the amplification factors estimated in this study are generally adequate ones. The effects of correction for site effects based on several methods are compared based on the changes in the standard deviation of the residuals of the corrected PGVs and the predicted ones, found that, (1) the empirical site factor derived in this studies gives better correction effect for site effect; (2) there are differences in correlation of site effects and Vs30 for the four regions, and these correlation also gives better correction effects.

INTRODUCTION

Evaluation of Site effect is very important in prediction of strong motion based on an empirical ground motion prediction equation (GMPE). Generally there are two methods usually used in site effect evaluation. The first one is the method based on the correlation between the site effects and Vs30, the average shear wave velocity in top 30 m (Borcherdt, 1992; Midorikawa et al., 1994; Boore et al., 1997; Fujimoto and Midorikawa, 2006). The other one is the empirical site effects estimated based on the inversion or regression analysis using theoretical or empirical model (Iwata and Irikura, 1986, Yamamoto et al., 1995, Tinsley, 2004). For the first method, it is difficult to apply when the information of soil profile such as Vs30 are not available for the target site. For the second method, since the inversion or regression analysis needs advanced techniques and experiences, it is not convenient for the engineering application. For this reason, Si et al. (2010) has proposed a simple and convenient method to evaluate site effects for engineering usage based on the average operation of the ratio of observation data over the prediction by a reference GMPE defined on the engineering bedrock.

In this study, the method proposed by Si et al. (2010) are examined and applied to evaluate the site effects for peak ground velocity (PGV) at stations located in four seismically active regions selected in Japan. By comparing with the standard deviation of strong motion corrected for site effects with empirical site effect and several previous proposed correction methods, we try to find the method more effective for the site effects correction.

METHODOLOGY

<u>Analysis flow</u>

The analysis process is divided into five steps as shown in follows. (1) Apply Si et al. (2010) to evaluate the site effects at K-NET stations in four selected regions. (2) Comparing the empirical site effect-Vs30 relation with the previously proposed relationship between the site effects and Vs30. (4) Discuss the difference among the four regions in the relationship between site effects and Vs30. (5) Searching the best method for site effect correction.

A simple method for site effect evaluation

Si et al. (2010) assumed that if seismic source and the path effect can be represented by the reference attenuation model, the site effect correction factor $R(\omega)$ can be estimate by averaging the residuals between the observation and prediction of a reference GMPE at an individual station. In this study, however, we use geometrical average as shown as Eq. (1) instead of arithmetic mean used in Si et al. (2010).

$$R(\omega) = \left(\prod_{i=1}^{n} \left(O(\omega) / O'(\omega) \right) \right)^{1/n} = \left(\prod_{i=1}^{n} \left(G(\omega) / G'(\omega) + \varepsilon_i \right) \right)^{1/n} \tag{1}$$

where, *O(ω)* is the observation records, *O'(ω)* is the prediction by a reference GMPE defined on the engineering bedrock, *i* is a specific record from an earthquake, *n* is the total number of the records used in estimation of the site effects. Since ε_i is a random number, with the increase of records in a station, the term $\Sigma\varepsilon_i /n$ getting to be smaller. This means that R (ω) can represent the site effects if there are sufficient records.

In equation (1), the attenuation relation for PGV proposed by Si and Midorikawa (1999, 2000) is selected as the reference GMPE. This attenuation model has been verified with many independent studies and is currently being used the national earthquake early warning system for predicting intensities through estimating PGVs. The model for PGV is defined on the engineering bedrock with a shear-wave velocity of about 600 m/s. The adopted reference attenuation equation is expressed below.

$$\log PGV = 0.58\, M_w + 0.0038D + d - \log(X + 0.0028 \cdot 10^{0.5M_w}) - 0.002\, X - 1.29 \tag{2}$$

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.

Correction of site effects for a GMPE

Then predicted PGV can be corrected with to reduce the epistemic uncertainty of site as;

$$\log PGV = \log(PGV') - \log(R) \tag{3}$$

With this correction, uncertainty of site effect can be reduced.

DATA

We selected four regions seismically active and prone to earthquake disaster. Earthquakes had occurred in/around these areas and stations are selected using the following selection criteria:

1) JMA magnitude (M_{JMA}) is greater than or equal to 4.0;
2) Events of focal depth less than 30 km, but less than 80 km for Kanto region (Area 3);
3) Stations with a hypocentral distance less than 100 km and a PGA exceeding 10 cm/s^2;
4) Events for which the attenuation characteristics are generally consistent with the reference ground motion attenuation model, meaning that the source and path effect can be represented by the reference ground motion attenuation model.

Selected areas and the epicenters of the earthquakes used in this study are indicated in Figure 1. Totally 178 earthquakes occurred from 1997 to 2010 are used in the analysis. Except for Area 3, all earthquakes are crustal event. In the Kanto region, out of 44 earthquakes, 3 are crustal, 30 are inter-plate and 11 are intra-plate events. Moment magnitudes of all events were obtained from F-net. Stations with more than 10 records were used in the analysis, while for Area 2 the cut line is set to 7 records due to the lack of events. Observation stations of K-NET investigated in this study for each region are shown in Figure 2. Triangles with light grays indicate stations that recorded less than three events, dark grays recorded 3 or 4 events, blue recorded 5 to 9 events, and green triangles recorded more than 9 events. Finally 84 stations out of 540 stations, matching the criteria, were used in the analysis.

Data distributions with respect to distance and magnitude for each area are shown in Figure 3. 3123 records are selected from 10,237 records from the 178 events. Magnitude, depth, hypocentral distance, peak ground acceleration, and velocity ranges are shown in Tables 1 and2. Peak velocity is defined as the larger one of two orthogonal horizontal components in the time domain processed by a band-pass filter with cut-off frequencies of 0.1 and 10 Hz. Hypocentral distances were accepted as closest distances for the attenuation model, since for small earthquake the two distances are almost the same.

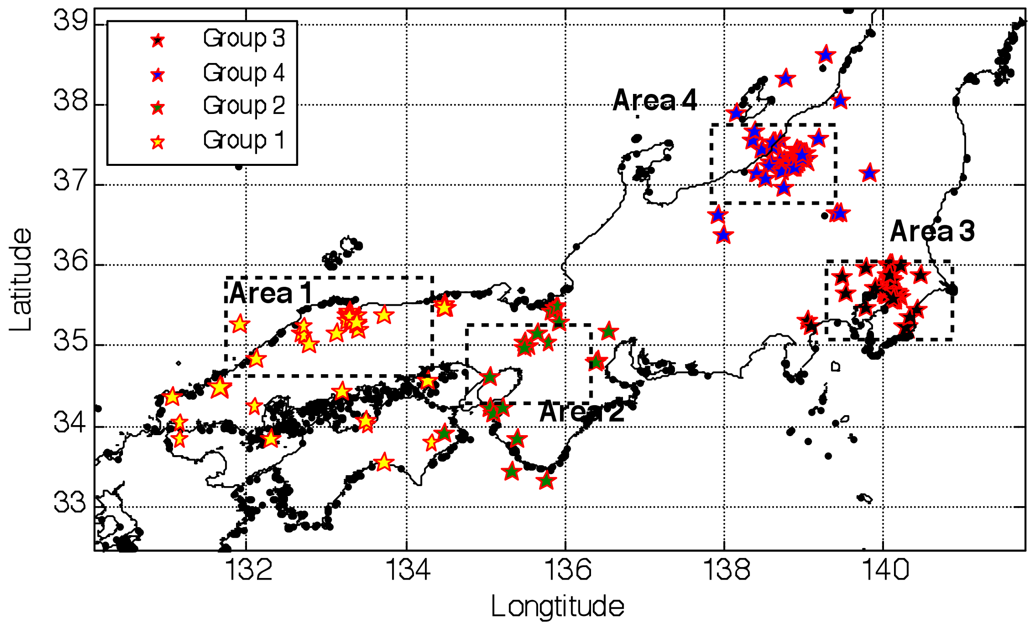

Fig. 1. Map showing epicenters and the areas investigated in this study. Groups 1-4 of the earthquakes correspond to areas 1-4. Area 1 represents Tottori and Chugoku, Area2 Kinki, Area 3 Kanto, and Area4 is Chuetsu regions. Numbers of earthquakes are 46, 27, 44, and 61 in each region, respectively.

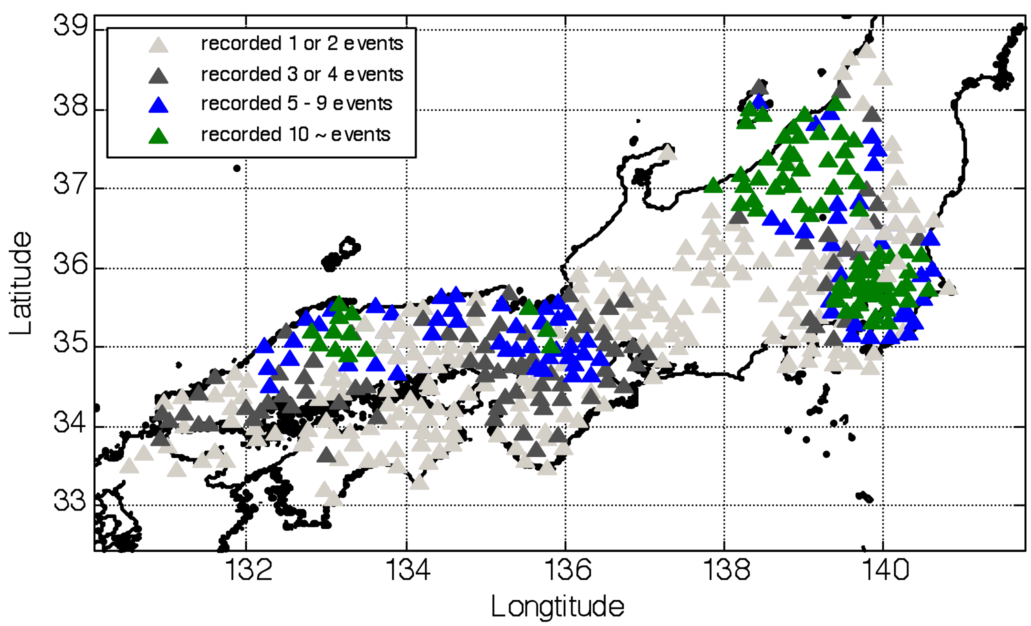

Fig. 2. K-NET stations in/around four regions. Various colors indicate number of recorded event in individual stations. Green colored stations are targeted sites in this study.

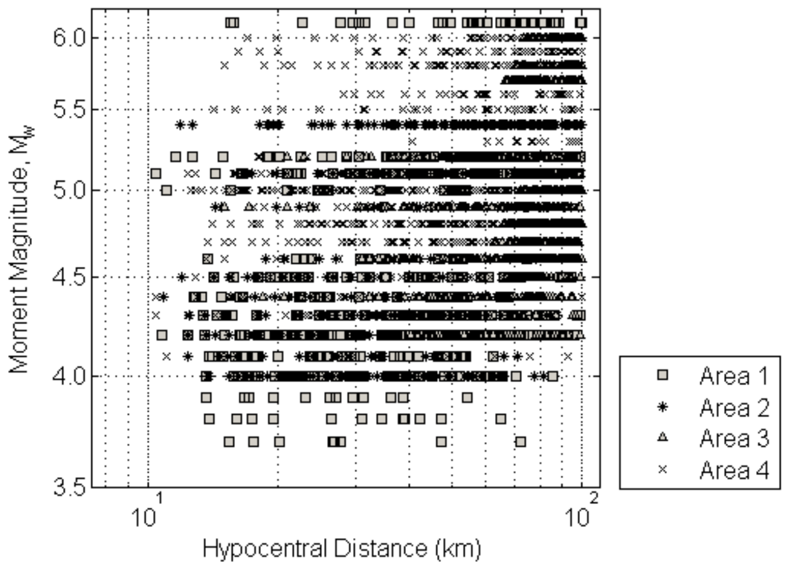

Fig. 3. Distribution of data with respect to magnitude and distance for four areas.

Table 1. Number of records and earthquakes used in this study

	Total records	Filtered records	Total stations	Stations	Earthquakes
Area 1	1996	536	150	12	46
Area 2	1767	472	165	3	27
Area 3	1756	1189	124	35	44
Area 4	4718	926	101	34	61
Total	10237	3123	540	100	178

Table 2. Data range list

	Magnitude Range	Depth range (km)	Epicentral Distance range (km)	PGA range (cm/s^2)	PGV range (cm/s^2)
Area 1	3.7-6.1	6-20	10.5-99.6	3.9-421.4	0.04-14.74
Area 2	4.0-5.4	3-25	5.6-99.9	7.2-715.7	0.08-33.71
Area 3	4.2-6.0	14-78	15.0-99.9	3.5-203.8	0.11-21.06
Area 4	4.0-6.0	1-28	10.4-100.0	6.1-544.6	0.05-43.78

RESULTS

Derived site effect for each station

Figure 4 shows the site effects, e.g., the mean residual between the observation and the prediction, derived in this study at each station as the red marks. In the figure, the residual for every earthquake used in this study and their bias at each station are also plotted. All the results are listed in Table 3, including the station's name, empirical correction factors, number of records and Vs30 information. Each station has its station ID, both shown in Figure 4 and Table 3. Since many stations of K-NET the Vs30 cannot be available directly, Vs30 for K-NET station are estimated from the correlation between Vs20 and Vs30 (Ghasemi, 2010). Figure 5 shows distribution of the mean residual and standard deviation of the residuals versus the number of records per station. From Figure 5, the standard deviation clearly decreases with the number of records per station, showing the method used for the evaluation of site effects is reasonable.

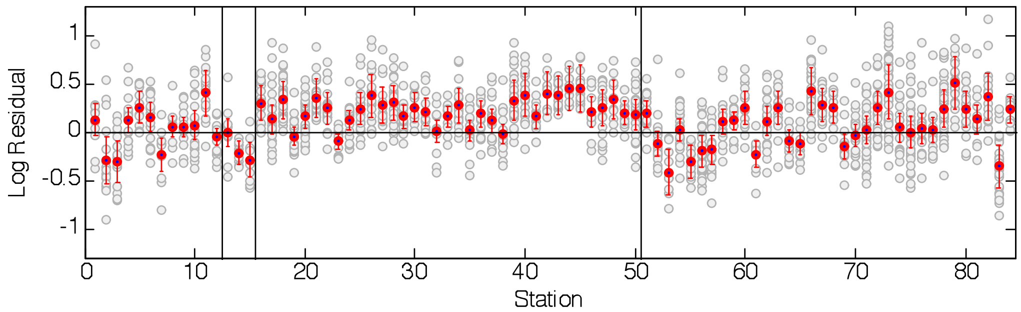

Fig. 4. Mean residuals with standard error at each station. Stations that have more than 10 records (green triangles in Figure 2.) Four regions are analyzed where 12, 3, 50 and 35 stations are selected respectively. In order to improve number of stations, limit is decrease to 7 records in Area 2. Red points are mean values with blue lines shows +1 standard deviation. Detailed information of stations is given in Table 3.

a) b)

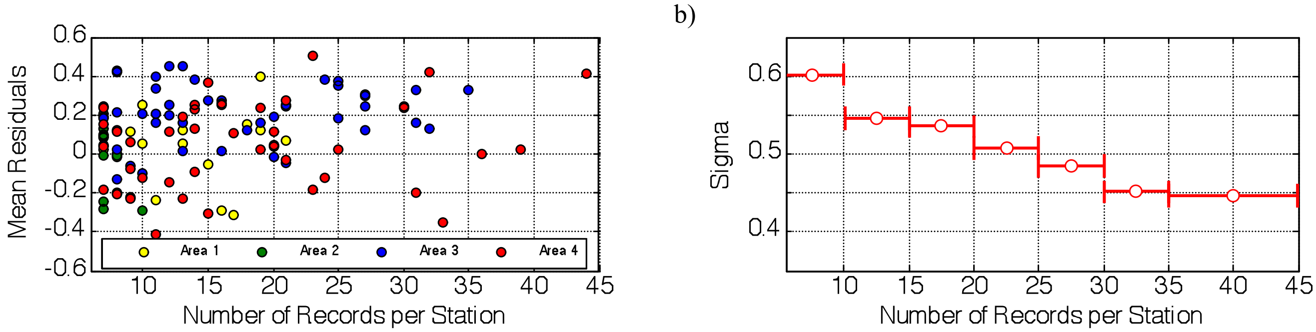

Fig. 5. a) Single station residuals vs. number of records per station at four region and b) single station standard deviation (Sigma) vs. number of records per station.

<u>Correlation between site effect and Vs30</u>

In Figure 6, the correlation between the site effect (refer as CF hereafter) derived in this study. The plots change their colors correspondent with stations located in different region. In the figure, the equations of amplification and Vs30 proposed by Midorikawa et al. (1994) and Fujimoto and Midorikawa (2006) are also shown in Figure 6. The results in this study are generally consistent with the past studies, showing the method proposed in this study is generally adequate.
For the discussion of the difference among the regions in correlation between the site effects and Vs30, the relationship for each region is derived based on a regression analysis. The results are shown in Figure 7 and eq (4) – eq (7). Areas 1 and 3 have the same slope, while Area 2 have biggest slope. Since the data in Area 2 seems to be not enough, however, it can't be concluded that the Area 2 is different from the others. Dependency of amplification factor on Vs30 by Midorikawa et al. (1994) is familiar with Areas 1, 3, and 4, but stronger one by Fujimoto and Midorikawa (2006).

$$\log(G)= 1.85-0.71.*\log10(Vs30) \tag{4}$$

$$\log(G)= 2.17- 0.92.*\log10(Vs30) \tag{5}$$

$$\log(G)= 1.82- 0.68.*\log10(Vs30) \tag{6}$$

$$\log(G)= 2.22- 0.86.*\log10(Vs30) \tag{7}$$

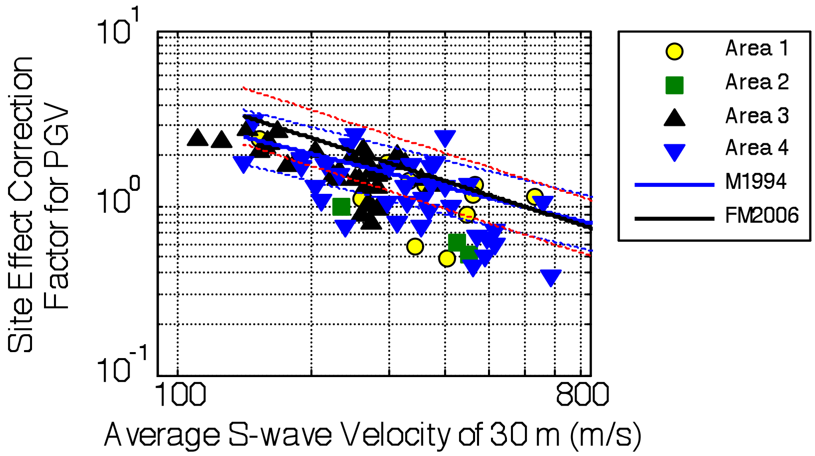

Fig. 6. Variation of correction factor with average S-wave velocity of top 30m. Color indicates the stations average correction factor respect to each area. Red and black lines are the relationships and +1 standard deviations of Midorikawa et al. (1994)[M1994 in the figure] and Fujiwara and Midorikawa (2006) [FM2006 in the figure].

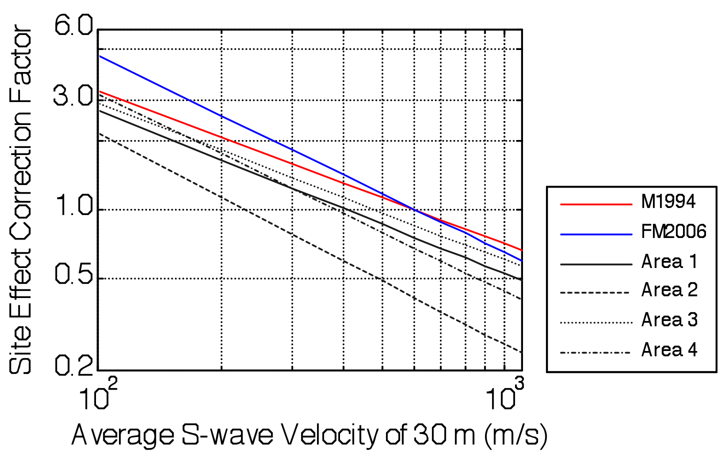

Fig. 7. Site specific relations with Vs30 and site effect correction factor.

<u>Comparison the modification effect for the three methods</u>

Figure 8 shows the standard deviations of the residuals of observation over prediction for four regions when the observation data are corrected for site effects by 3 correction methods based on, (1) empirical correction factor derived in this study (b) in Figure 8; (2) correlation between the amplification factor and Vs30 proposed by Midorikawa et al. (1994) (c), and Fujimoto and Midorikawa (2006) (d). Generally if the site effect correction is effective, the standard deviation of the residuals will be reduced. It can be confirmed that, (1) the correction based on the empirical correction factor derived in this study gives smallest standard deviation; (2) Midorikawa et al. (1994) and Fujimoto and Midorikawa (2006) also reduce the standard deviation effectively.

Figure 9 shows the reduction of standard deviation for four regions for which the data was corrected by regions specific Vs30 based relationship defined in Equations from 4 to 7. By comparing with the results shown in Figure 8, it can be found that the results based on regions specific Vs30 based relationship gives lower standard deviation then the results based on nation-wide Vs30 based relationship between the amplification factor and Vs30.

For the empirical amplification factor, however, since the reduction of correction effect for site effect may be come from the trade off during the process of estimation-correction-of-site-effect, we check it based on the analysis on the database additional to those used in development of the empirical amplification factors, and found that the results showing no significant changes. This means that the empirical amplification factor derived by the method used in this study are relatively stable ones.

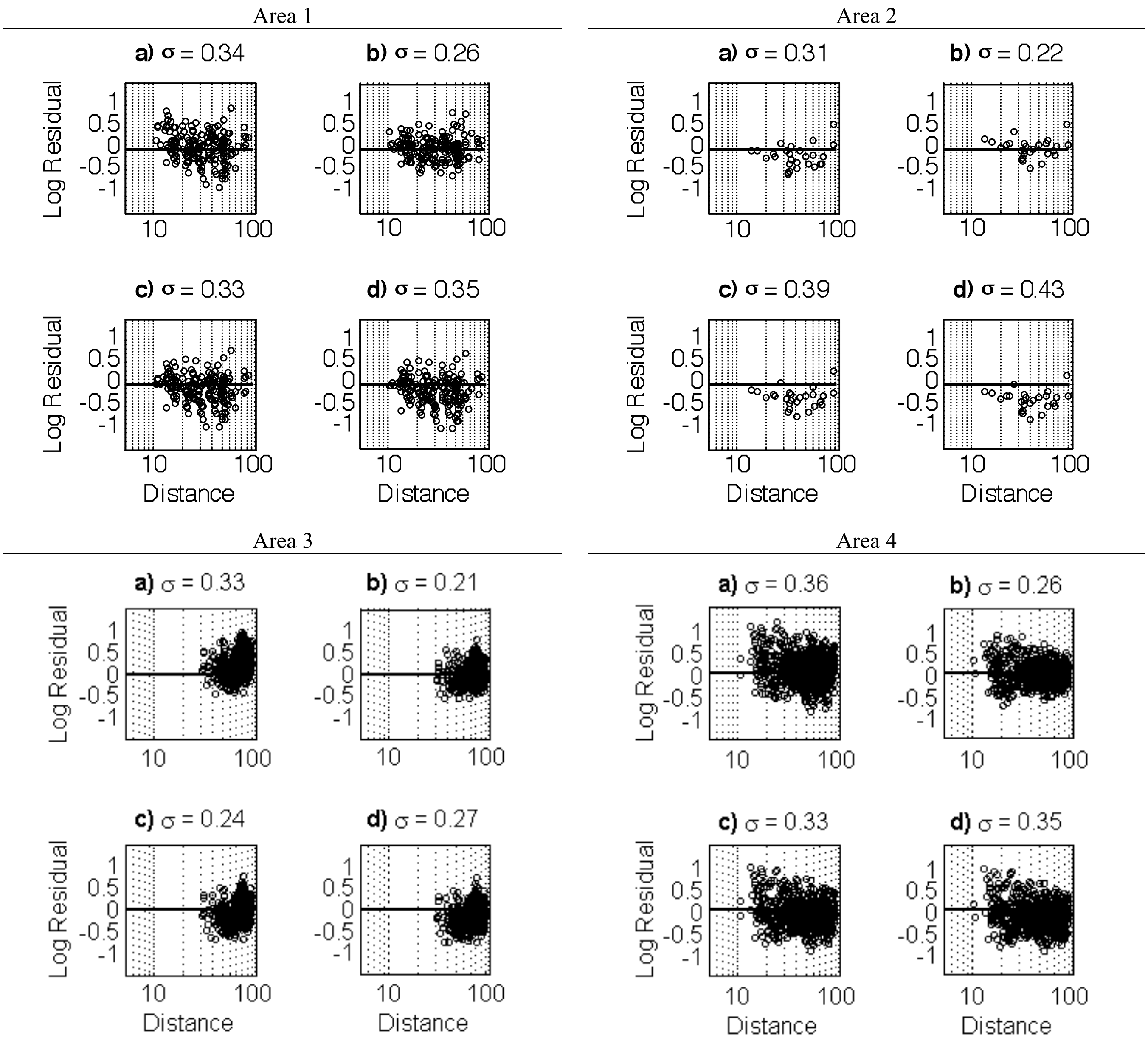

Fig. 8. Residuals of selected station at four regions a) without any correction b) empirical-amplification-corrected c) corrected with Midorikawa et al. (1994), and d) Fujimoto and Midorikawa(2006)

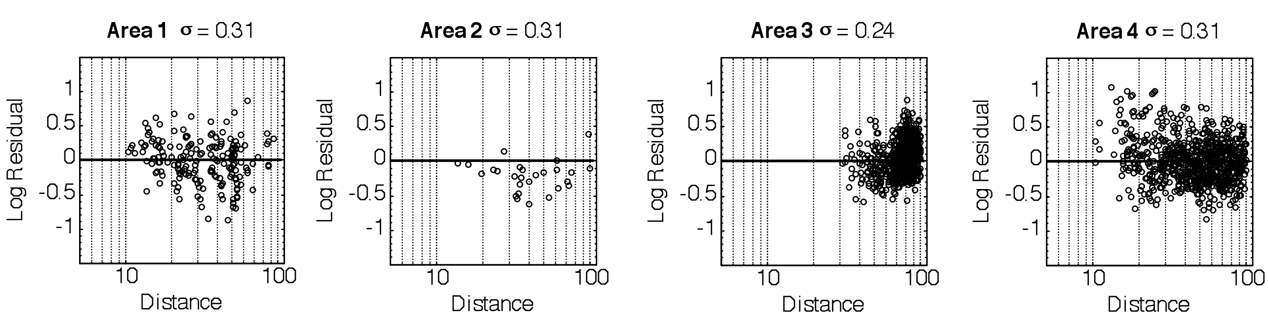

Fig. 9. Residuals and standard deviation of four regions after corrected with region specific Vs30 based relationship.

Table 3. Parameters and results for each station

Station No	Station Name	No. of Records	Empirical CF	Vs30 m/s
Area 1				
1	HRS001'	13	1.79	358
2	'HRS002'	16	0.79	449
3	'HRS021'	17	0.6	403
4	'OKY004'	19	1.53	466
5	'OKY005'	10	1.98	295
6	'SMN001'	18	1.65	330
7	'SMN003'	11	0.68	342
8	'SMN015'	10	1.27	634
9	'SMN016'	13	1.25	259
10	'TTR007'	21	1.49	460
11	'TTR008'	19	2.94	153
12	'TTR009'	15	0.96	446
Area 2				
13	'FKI010'	8	1.26	232
14	'KYT010'	9	0.62	422
15	'KYT012'	10	0.58	449
Area 3				
16	'CHB001'	27	2.17	245
17	'CHB002'	32	1.71	376
18	'CHB003'	35	2.41	204
19	'CHB006'	21	0.98	258
20	'CHB007'	31	1.58	255
21	'CHB008'	25	2.49	158
22	'CHB009'	21	2.02	177
23	'CHB010'	10	0.83	273
24	'CHB012'	18	1.42	264
25	'CHB014'	27	1.98	181
26	'CHB015'	25	2.82	161
27	'CHB017'	15	2.26	263
28	'CHB022'	27	2.25	312
Area 3				
29	'CHB024'	19	1.6	251
30	'IBR005'	12	1.9	305
31	'IBR010'	11	1.83	230
32	'IBR011'	13	1.16	268
33	'IBR012'	11	1.52	228
34	'IBR013'	16	2.2	265
35	'IBR014'	16	1.16	270
36	'IBR015'	20	1.68	223
37	'IBR016'	27	1.5	280
38	'IBR017'	20	1.09	282
39	'KNG001'	31	2.53	152
40	'KNG002'	24	2.77	126
41	'KNG006'	13	1.57	351
42	'SIT003'	11	2.76	111
43	'SIT008'	14	2.51	159
44	'SIT010'	12	2.94	167
45	'SIT011'	13	3.09	144
46	'SIT013'	10	1.86	272
47	'TKY004'	21	2.13	324
48	'TKY005'	11	2.46	262
49	'TKY006'	12	1.67	287
50	'TKY007'	25	1.82	282
Area 4				
51	'FKS022'	13	1.7	230
52	'FKS026'	24	0.94	354
53	'FKS027'	11	0.44	690
54	'FKS028'	25	1.23	328
55	'FKS030'	15	0.53	489
56	'GNM001'	31	0.77	494
57	'GNM002'	23	0.75	469
Area 4				
58	'GNM003'	17	1.52	398
59	'NGN001'	12	1.39	326
60	'NGN002'	14	2.05	380
61	'NGN003'	13	0.63	515
62	'NIG003'	20	1.57	204
63	'NIG004'	16	2.04	333
64	'NIG005'	14	0.9	310
65	'NIG008'	10	0.84	239
66	'NIG012'	32	3.05	250
67	'NIG013'	21	2.15	191
68	'NIG014'	16	1.97	141
69	'NIG015'	12	0.82	516
70	'NIG016'	21	1.08	366
71	'NIG017'	39	1.31	295
72	'NIG018'	30	2.06	216
73	'NIG019'	44	3.66	397
74	'NIG020'	20	1.43	355
75	'NIG021'	36	1.36	411
76	'NIG022'	20	1.49	210
77	'NIG023'	19	1.34	661
78	'NIG024'	30	2.19	371
79	'NIG025'	23	3.61	148
80	'NIG026'	19	2.11	298
81	'NIG027'	14	1.68	371
82	'TCG009'	15	3.28	244
83	'FKS029'	33	0.54	458
84	'NIG010'	14	1.8	189

CONCLUSIONS

The site effects at stations located in four regions are estimated using an empirical evaluation method proposed by Si et al. (2010). We examined the results by comparing the correlation between the site effects and the Vs30 derived in this study with the past studies, and found that the results are generally consistent, implicating that the amplification factors estimated in this study are generally adequate ones. The effects of correction for site effects based on several methods are compared based on the changes in the standard deviation of the residuals of the corrected PGVs and the predicted ones, found that, (1) the empirical site factor derived in this studies gives better correction effect for site effect; (2) there are differences in correlation of site effects and Vs30 for the four regions, and these correlation also gives better correction effects.

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