SIMPLIFIED METHOD FOR PREDICTING AVERAGE SHEAR-WAVE VELOCITY OF GROUND AT STRONG-MOTION STATIONS

K. Fujimoto[1] and S. Midorikawa[2]

[1] *Lecturer, Dept. of Risk and Crisis Management System, Chiba Institute of Science, Chiba, Japan*
[2] *Professor, Dept. of Built Environment, Tokyo Institute of Technology, Kanagawa, Japan*
Email: kfujimoto@cis.ac.jp, smidorik@enveng.titech.ac.jp

ABSTRACT :

We develop a method for estimating average shear-wave velocity in the upper 30 meters of the ground (V_S30) at a strong-motion station by using recorded motions at a pair of stations located closely each other. For the station pair, an estimate of V_S30 at one of the stations where the soil condition is unknown is derived mainly from V_S30 at another station where the shear-wave velocity data is available and relative amplification factor between the stations. By applying this method to the ground motion records of the JMA, K-NET and KiK-net strong-motion networks in Japan, the V_S30 values are estimated at 261 JMA strong-motion stations throughout Japan. The V_S30 estimated in this study are compared with those inferred from boring data obtained in the vicinity of the JMA station. The result indicates that the method proposed in this study can predict the V_S30 values at a strong-motion station with an accuracy of approximately +/- 50 m/sec. As the additional validation, correlations are examined between the estimated V_S30 and the site classification at the JMA stations, and between the predicted peak ground velocities from the estimated V_S30 and the observed ones for Japanese recent major earthquakes. The results indicate the validity of the estimated V_S30 values.

KEYWORDS: average shear-wave velocity, strong-motion station, JMA, K-NET, KiK-net

1. INTRODUCTION

In Japan, nationwide strong-motion seismograph networks, e.g., the K-NET and KiK-net of the National Research Institute for Earth Science and Disaster Prevention (NIED) and the 95-type seismometer network of the Japan Meteorological Agency (JMA) have been operated. Borehole shear-wave velocity logs are available at all of the K-NET and KiK-net stations while the soil condition at the JMA station is not investigated. Therefore, it is difficult to analyze the strong-motion records obtained at the JMA station considering the local site condition. To classify the local site condition, average shear-wave velocity to a certain depth of the ground has been widely used (Borcherdt, 1978). Especially, average shear-wave velocity in the upper 30 meters (V_S30) is mostly in practical use in classification of surface geological unit which is utilized in the National Seismic Hazard Mapping Project in Japan (Fujiwara et al., 2004) and in U.S. building codes (Borcherdt, 1994).

Value of V_S30 at a site can be computed from geotechnical data, such as velocity logging and boring log, or estimated from microtremor array observation (Konno and Kataoka, 2000). However, to obtain these data over a wide area, much time and labor are required because the data necessitate on-site drilling or measurement. The estimate of V_S30 can be also obtained from surface geology in the nationwide geomorphologic database in Japan (Fujimoto and Midorikawa, 2004; Matsuoka et al., 2006). Furthermore, Wald and Allen (2007) derived the global V_S30 map directly from 30 arc sec topographic data. Since the mesh size used in these studies is about 1km by 1km, V_S30 estimates from such mapped geology may differ from actual V_S30 at a site.

In this study, we develop a simple method for estimating V_S30 at a strong-motion station mainly derived from peak ground motions recorded at a pair of stations located closely each other. By applying the method to the recordings obtained at the K-NET, KiK-net and JMA networks throughout Japan, V_S30 values at the JMA strong-motion stations are estimated. To examine the estimation accuracy of the V_S30, predicted V_S30 values from the method are compared with those inferred from boring data obtained in the vicinity of the JMA station, site classification at the JMA station, and seismic ground motion records during recent major earthquakes.

2. METHOD AND DATASET

2.1. Method

We explain a method for estimating V_S30 at a strong-motion station. As illustrated in Figure 1, for a pair of strong-motion station located closely each other, shear-wave velocity profile is available at one station ("known station") that is not obtained at another station ("unknown station"). During a certain earthquake, peak ground velocities recorded at known and unknown stations are referred to as PGV_k and PGV_u, respectively. Peak amplitude ratio corrected by the reciprocal ratio of hypocentral distances for the station pair provides a relative amplification factor (AF').

$$AF' = (PGV_u/PGV_k)(X_u/X_k) \tag{2.1}$$

where X_k and X_u are the distances from an hypocenter to known and unknown stations, respectively. Fujimoto and Midorikawa (2006) showed seismic site amplification factor (AF) decreases with an increase in V_S30 with slope b on average based on the ground motion records and V_S30 measurements at the K-NET and KiK-net. Therefore, V_S30 value at unknown station (V_S30_u) can be expressed by Eqn. 2.2.

$$\log V_S30_u = \log V_S30_k + \log AF'/b \tag{2.2}$$

where V_S30_k is average shear-wave velocity at known station computed from measured shear-wave velocity profile. Thus, we can obtain V_S30 estimate at a strong-motion station not having shear-wave velocity data by substituting AF', V_S30_k, and b into Eqn. 2.2.

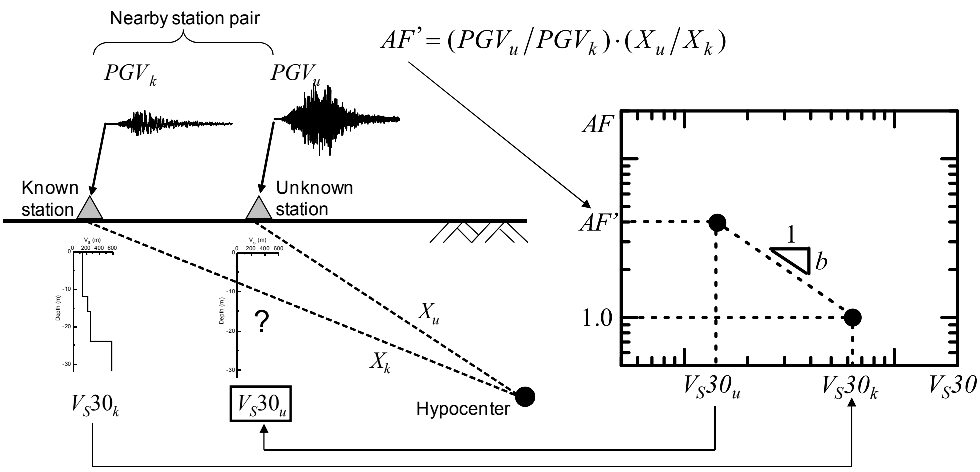

Figure 1 Schematic diagram of prediction method

2.2. Dataset

K-NET and KiK-net are the nationwide strong-motion seismograph networks consisted of 1,001 and 495 stations with a spacing of 25 km averagely. Japan Meteorological Agency (JMA) also has nationwide strong-motion network consisted of 602 stations. Combination of these strong-motion networks offers the opportunity to pair nearby strong-motion stations. Borehole shear-wave velocity data is available at all of the K-NET and KiK-net stations however that is not investigated at the JMA station. Thus, we adopt the K-NET and KiK-net stations as the "known station" and the JMA station as the "unknown station" in this study. We can compute V_S30 values at 758 known stations and use these values as V_S30_k. Figure 2 shows the location of the K-NET and KiK-net stations (known station) by closed circles.

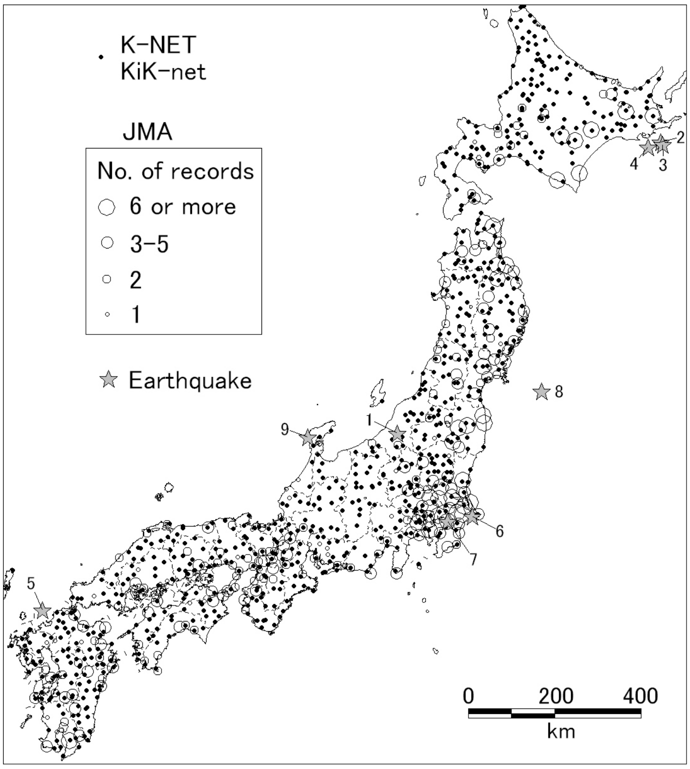

Figure 2 Location of K-NET, KiK-net and JMA stations

To pair the JMA station (unknown station) with the K-NET or KiK-net stations (known stations), station-to-station distances between the JMA station and both the K-NET and KiK-net stations are calculated, and then each JMA station is paired with one of the nearest K-NET or KiK-net station. Since the propagation path effect is considered to be not negligible for station distance greater than about 30 km (Borcherdt, 2002), the station pair with station distance of more than 30 km are excluded. Consequently, 339 known-unknown station pairs are made. For the station pairs, ground motion records of the earthquakes occurred up until December, 2003 with peak ground accelerations of less than 100 gals are collected. Common recordings obtained at both the known and unknown stations are necessary to compute *AF*' value however such records are not available at 57 station pairs. Therefore, 282 station pairs are used in the subsequent analysis. The location of the paired JMA stations is shown by open circles in Figure 2.

A histogram showing the number of common recordings obtained at a total of 282 known-unknown pairs is shown in Figure 3. Station pairs with common records less than 2 and 5 earthquakes account for about 40% and 80% of the total pairs, respectively. Figure 4 shows the histogram of the distance between the known and unknown stations. The number of station pairs tends to increase as the station pair distance becomes shorter. Station pair distance less than 5 km makes up about 30% of the total pairs.

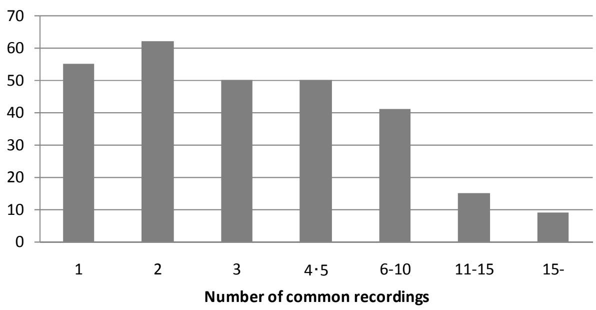

Figure 3 Histogram of number of common records

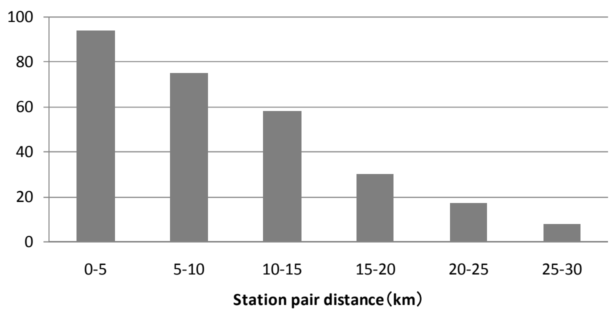

Figure 4 Histogram of station pair distance

3. ESTIMATES OF Vs30 AT JMA STATIONS

For the 282 known-unknown station pairs, relative amplification factors (*AF*') are calculated by substituting peak ground velocities (*PGV*) and hypocentral distances into Eqn. 2.1. The *PGV* is adopted as the ground motion parameter in Eqn. 2.1 because this parameter shows better correlation with V_S30 than does *PGA* (Fujimoto and Midorikawa, 2006). Value of *AF*' is defined as the largest value of the corresponding quantity computed from the two horizontal components obtained at each station pair. Substituting the *AF'* together with average shear-wave velocity at known station (V_S30_k) and average value of slope *b* specified as -0.852 (Fujimoto and Midorikawa, 2006) into Eqn. 2.2, we obtain the V_S30 estimate at the JMA stations.

Figure 5 shows the correlation between the estimated V_S30 and magnitude (M) for each paired JMA station. The estimated V_S30 remains relatively constant at most of the stations however a large scatter of the V_S30 is found at the paired station with the recordings from the earthquake of magnitudes 5.0 or less, e.g., the JMA Urakawa [D62], Kuki [51E] and Yonago [EA0]. The *PGV* which is used to compute the *AF*' correlates better with ground motion over a mid-period range (0.5-2.0 sec) (Kobayashi and Nagahashi, 1973), however mid-period motions are less dominant in the records from the earthquakes with smaller magnitude than are short-period motion. Therefore, the variance of *AF*' may increase as magnitude of the earthquake becomes smaller. Consequently, Value of V_S30_u are estimated by substituting the *AF*' computed from records with M>5.0 into Eqn. 2.2.

Figure 6 shows the distribution of predicted V_S30 values at 261 JMA stations. For reference, average V_S30 values computed from the records with M>5.0 are shown by dotted line in Figure 5. As shown in Figure 6, many of low V_S30 stations are located on alluvial plain such as Kanto and Osaka Plains. Figure 7 presents the histogram of V_S30 estimates. Predicted V_S30 reaches a peak around 200 m/sec, ranging widely from 100 m/sec of very soft soil to more than 600 m/sec of engineering bedrock.

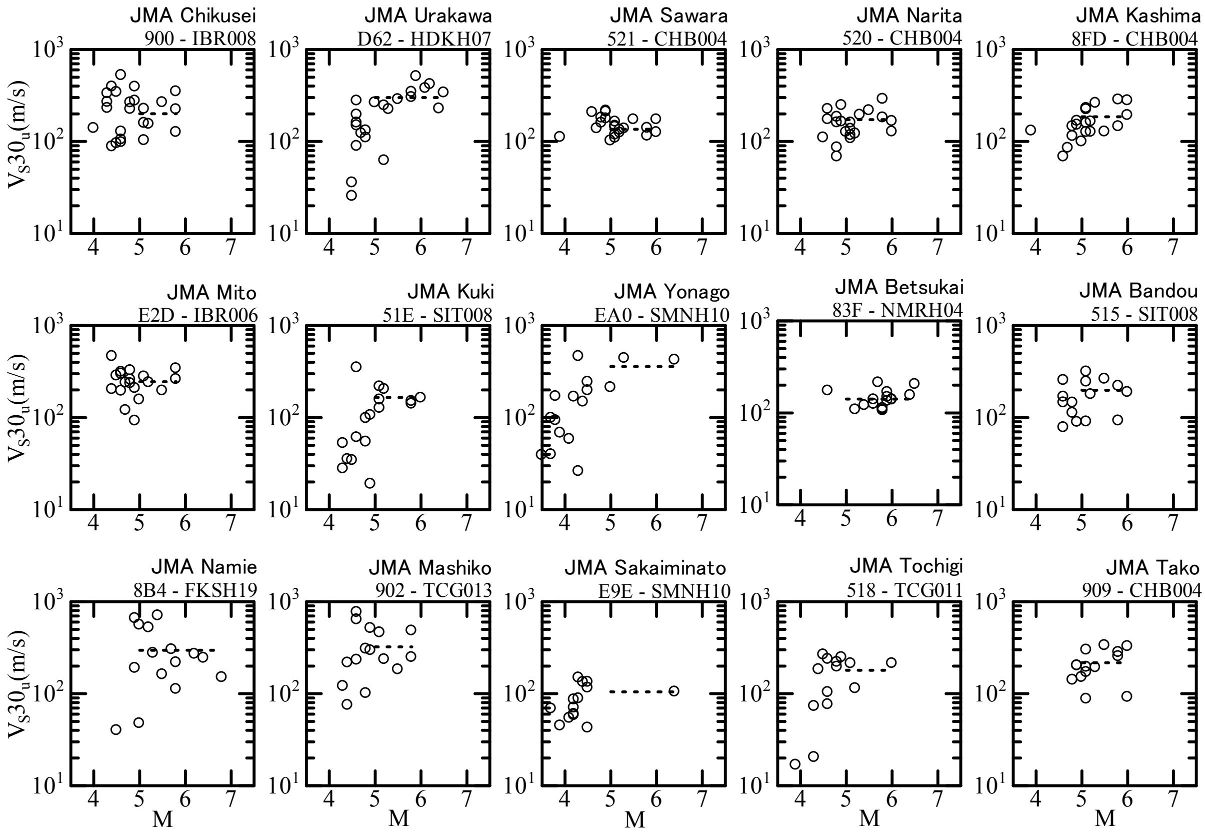

Figure 5 Correlation between V_S30 and magnitude

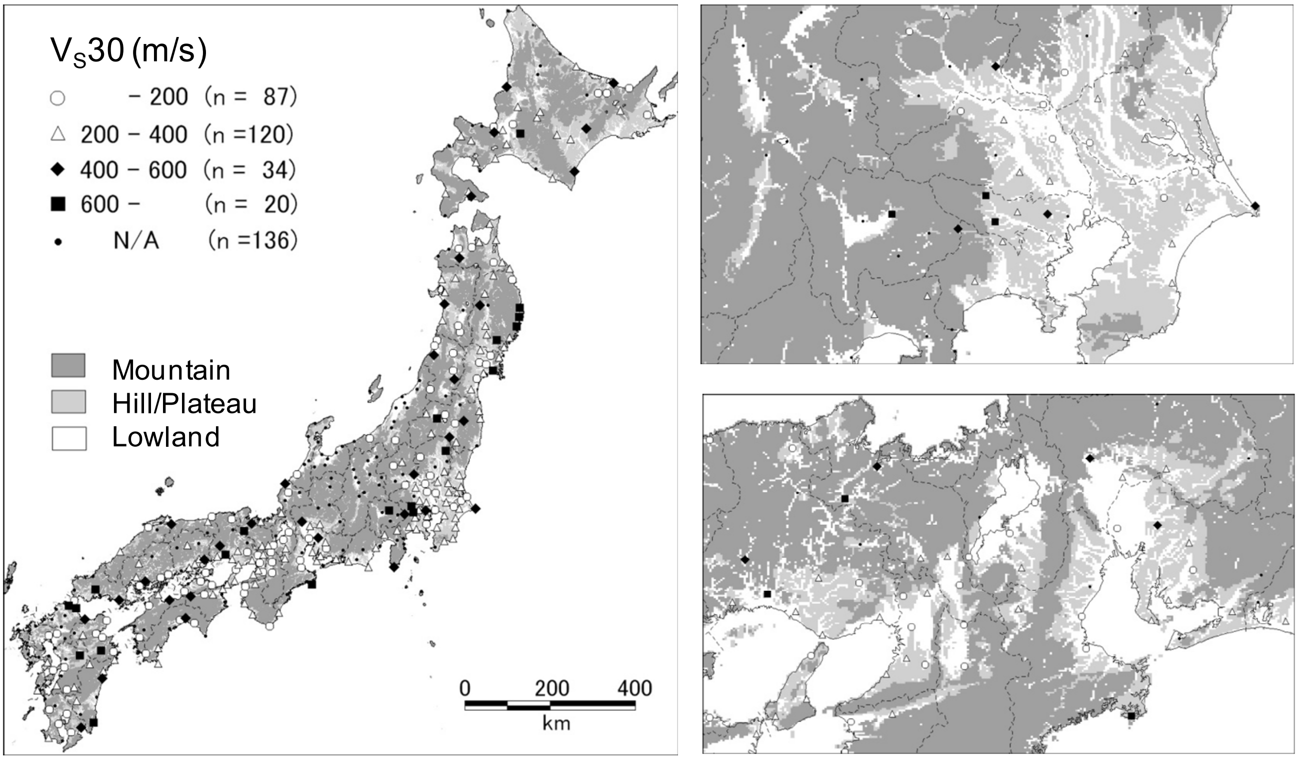

Figure 6 Distribution of V_S30 estimate at JMA stations
(left: national map, upper right: Kanto area map, lower right: Hanshin-Chukyo area map)

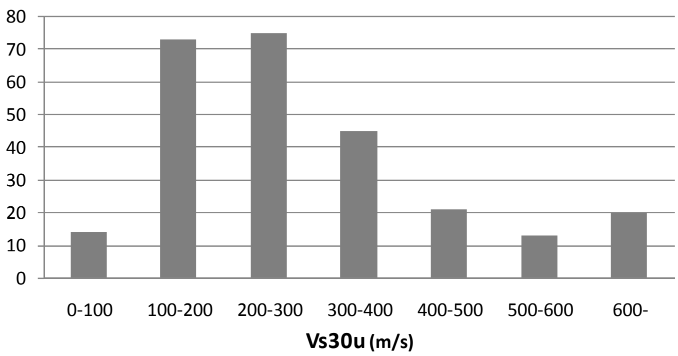

Figure 7 Histogram of V_S30 estimate at JMA stations

4. COMPARISON BETWEEN ESTIMATED AND OBSERVED V_S30

To examine the estimation accuracy of V_S30, boring logs with SPT N-value obtained in the vicinity of the JMA stations are compiled from several sources. We use 13 boring data that satisfies the following conditions: 1) drilling depth is 30 meters or more, 2) distance between the JMA station and borehole site is within 200 meters, 3) both the JMA station and borehole site are located on the same geomorphological unit. V_S30 values at the 13 boring sites near the JMA station are computed based on the shear-wave velocity model estimated from N-value and depth using the empirical equation (Ohta and Goto, 1978). Figure 8 shows a comparison of the V_S30 between the values predicted from the station-pair method and those estimated from adjacent boring data. The agreement between the predicted and estimated V_S30 is excellent. This result indicates that the method developed herein can predict the V_S30 at a strong-motion station with an accuracy of approximately +/- 50 m/sec.

To examine the applicability of the station-pair method for velocity range more than 300 m/sec, we compare the predicted V_S30 with site classifications at each JMA station. Site class at the JMA station was investigated (Yoshida and Katsumata, 1972), and each station was classified into four categories: 1) rock, 2) stiff soil, 3) soft soil, and 4) very soft soil. Figure 9 shows the histogram of the V_S30 for each site class. There appears to be a significant shift toward higher velocities as the site class becomes stiffer however relatively low velocites of less than 400 m/sec are seen at rock site. Several of the low V_S30 sites are located on weathered rock. Thus, underestimate of V_S30 at rock site may come from the overestimation of *AF'* due to the ground motion amplification from the low-velocity weathered layer.

To provide more rigorous validation for the station-pair method, we compare the predicted peak ground velocities with observeations during recent large earthquakes. We compute peak ground velocity (PGV) at the JMA station by multiplying the seismic site amplification converted from the estimated V_S30 using empirical equation (Fujimoto and Midorikawa, 2006) and the peak velocity on engineering bedrock predicted from attenuation relationship (Midorikawa and Ohtake, 2004). Correlation between the predicted and observed PGV at the JMA station is shown by closed circle in Figure 10. Likewise, the correlations for the K-NET and KiK-net stations are presented by open square and opne triangle, respectively. There is a good agreement between the predicted and observed PGV however the predicted values are underestimated for several earthquakes such as Eq. 2, 3, 4, and 8. As shown in Figure 2, these earthquakes were occurred in the north-east part of Japan, where the anomalous seismic intensity of subduction zone has been observed. This probably affects that the observed PGV show higher value compared to predicted one. Figure 11 shows the logarithmic standard deviations for the ratio of predicted and observed PGV. The standard deviation of the JMA station (closed circle) ranges 0.2-0.3, that is almost the same with those of the K-NET (open rectangle) and KiK-net (open triangle).

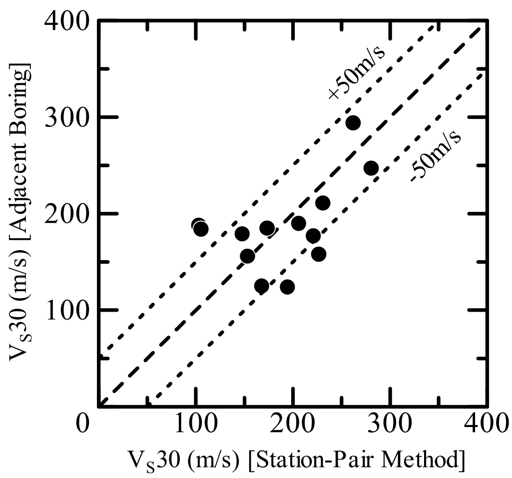

Figure 8 Comparion of V_S30

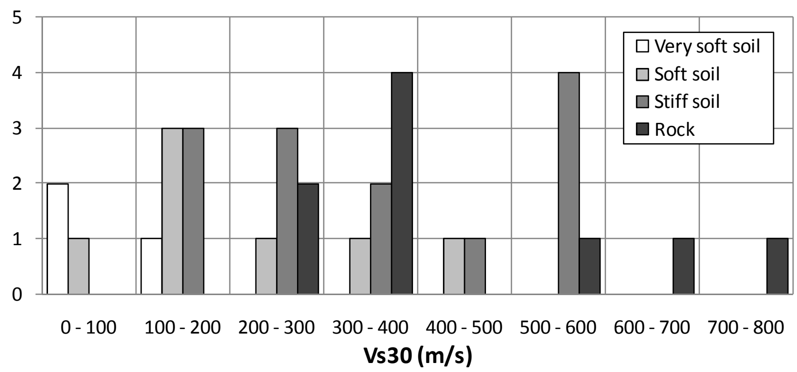

Figure 9 Histogram of V_S30 for each site class

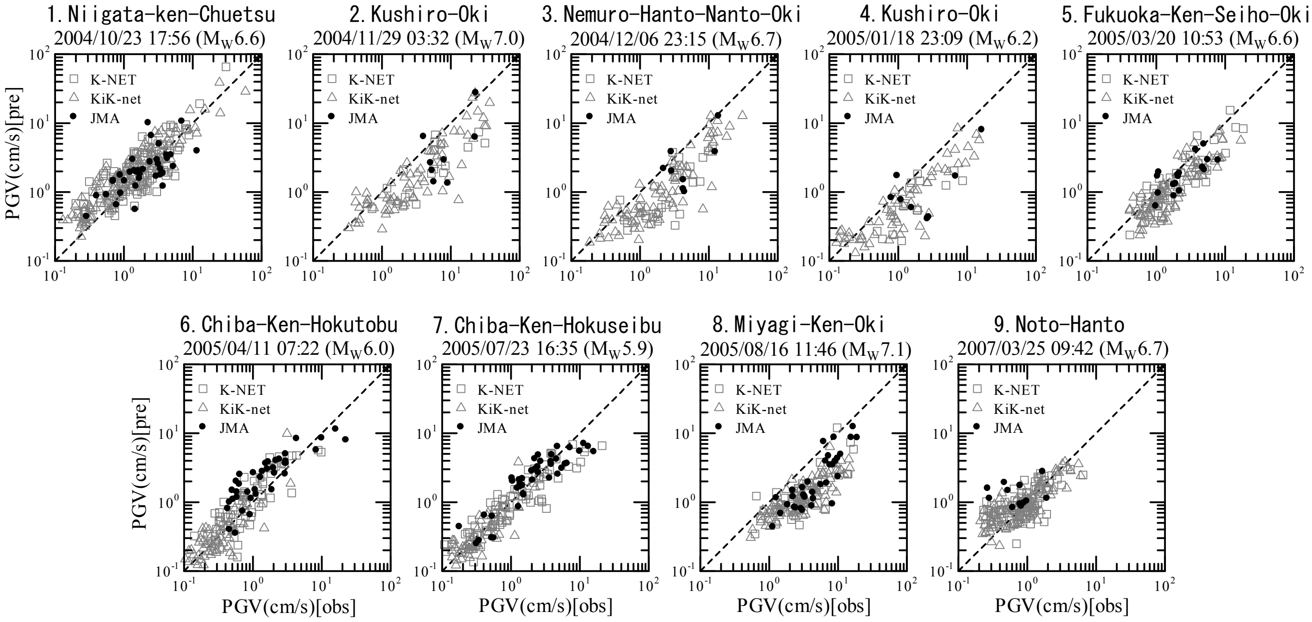

Figure 10 Comparison of PGV

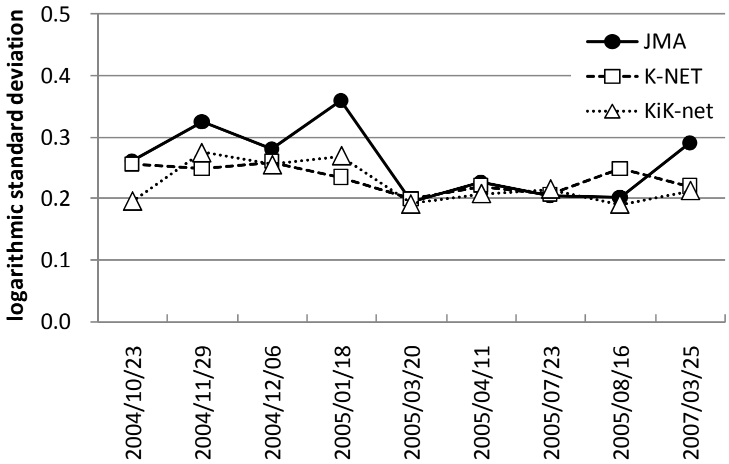

Figure 11 Comparison of logarithmic standard deviation

5. CONCLUSIONS

We develop a simple method for estimating average shear-wave velocity in the upper 30 meters of the ground (V_S30) at a strong-motion station by using recorded motions at a pair of stations located closely each other. For the station pair, an estimate of V_S30 at one of the stations where the soil condition is unknown is derived mainly from V_S30 at another station where the shear-wave velocity data is available and relative amplification factor between the stations. By applying this method to the ground motion records of the JMA, K-NET and KiK-net strong-motion networks in Japan, the V_S30 values are estimated at JMA stations. The estimated V_S30 remains relatively constant at most of the stations however a large scatter of V_S30 are found in some cases when using the recorded motions of magnitudes 5.0 or less. Therefore, using only the records of magnitude more than 5.0, the V_S30 values are recalculated at the 261 JMA stations throughout Japan.

The V_S30 estimated in this study are compared with those inferred from boring data obtained in the vicinity of the JMA station. The result indicates that the method proposed in this study can predict the V_S30 values at a strong-motion station with an accuracy of approximately +/- 50 m/sec. Relationship between V_S30 and four site classes such as rock, stiff soil, soft soil and very soft soil at each JMA station are examined. The resuts shows that there appears to be a significant shift toward higher velocities as the site class becomes stiffer. By multiplying seismic site amplification factors converted from the V_S30 estimated in this study and peak velocities on engineering bedrock predicted from attenuation relationship, peak ground velocities are computed. Compared with observed peak ground velocities for recent major nine earthquakes occurred in Japan, the computations show good agreement with observations.

REFERENCES

Borcherdt, R.D., Gibbs, J.F., and Fumal, T.E. (1978). Progress on ground motion predictions for the San Francisco Bay region, California, *Proc. of the 2nd International Conf. on Microzonation*, **1**, 241-253.

Borcherdt, R.D. (1994). Estimates of site-dependent response spectra for design (Methodology and Justification), *Earthquake Spectra*, **10**, 617-653.

Borcherdt, R.D. (2002). Empirical evidence for acceleration-dependent amplification factors, *Bull. Seism. Soc. Am.*, **82:2**, 603-641.

Fujimoto, K. and Midorikawa, S. (2004). Prediction of average shear-wave velocity for ground shaking mapping using the Digital National Land Information of Japan, *Proc. of the 13th World Conf. on Earthquake Engineering*, Paper No.1107.

Fujimoto, K. and Midorikawa, S. (2006). Empirical estimates of site amplification factor from strong-motion records at nearby station pairs, *Proc. of the 1st European Conf. on Earthquake Engineering and Seismology*, ID No. 251.

Fujiwara, H., Aoi, S., Kawai, S., Senna, S., Ishii, T., Okumura, T., and Hayakawa, Y. (2004). Outline of strong-motion evaluation in National Seismic Hazard Mapping Project of Japan, *Journal of Japan Association for Earthquake Engineering*, **4:3**, 50-61.

Kobayashi, H. and Nagahashi, S. (1973). Evaluation of earthquake effects on the deformation of multi-storied buildings by ground motion amplitudes, *Trans of A.I.J.*, 210, 11-22. (in Japanese with English abstract)

Konno, K. and Kataoka, S. (2000). New Method for Estimating The Average S-Wave Velocity of The Ground, *Proc. of the 6th International Conf. on Seismic Zonation*.

Matsuoka, M., Wakamatsu, K., Fujimoto, K., and Midorikawa, S. (2006). Average Shear-wave Velocity Mapping Using Japan Engineering Geomorphologic Classification Map, *Journal of Structural Engineering and Earthquake Engineering, Japan Society of Civil Engineers*, **23:1**, 57s-68s.

Midorikawa, S. and Ohtake, Y. (2004). Variance of peak ground acceleration and velocity in attenuation relationships, *Proc. of the 13th World Conf. on Earthquake Engineering*, Paper No.325.

Ohta, Y. and Goto, N. (1978). Physical background of the statistically obtained S wave velocity equation in terms of soil indexes, *Butsuri-Tanko (Geophysical Exploration)*, **31:1**, 8-17. (in Japanese with English abstract)

Yoshida, H. and Katsumata, M. (1972). Ground conditions of seismological stations in J.M.A. network, *Quarterly journal of seismology*, **37:3**, pp.113-115. (in Japanese)

Wald, D.J. and Allen, T.I. (2007). Topographic slope as a proxy for seismic site conditions and amplication, *Bull. Seism. Soc. Am.*, **97:5**, 1379-1395.