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Estimation of site amplification characteristics of response spectrum with respect to the average shear wave velocity

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ABSTRACT

In this study, the characteristics of site amplification at seismic observation stations in Japan were estimated using the attenuation relationship of each station's response spectrum. Ground motion records observed after 32 earthquakes were employed to construct the attenuation relationship. The station correction factor at each KiK-net station was compared to the transfer functions between the base rock and the surface. In addition, the station correction factors were evaluated with respect to the average shear wave velocities using a geographic information system (GIS) dataset. Lastly, the site amplifications for specific periods were estimated throughout Japan.

1. INTRODUCTION

Ground motion observed at the surface is affected by different influences such as the source characteristics, the propagation path, and the amplification characteristics of the ground surface. The site amplification characteristics affect the intensity of ground motion, and peak ground accelerations (PGAs) and peak ground velocities (PGVs) are mainly used to show the intensity. In addition to the intensity of ground motion represented by the PGA and PGV, the periodic contents of ground shaking are also important for evaluating the damage to structures after a large earthquake.

The amplification characteristics of the ground surface has been estimated in several studies for specific geographical areas of Japan as well as the entire area of Japan based on land classifications (Matsuoka and Midorikawa 1995; Shimizu et al. 2006; Yamazaki et al. 2000). It is revealed that the amplification factors are correlated with the average shear wave velocity from the surface to a certain depth. The shear wave velocity averaged over the upper 30 m (AVS30) is used for soil classification in the seismic design code in the United States (BSSC 2009).

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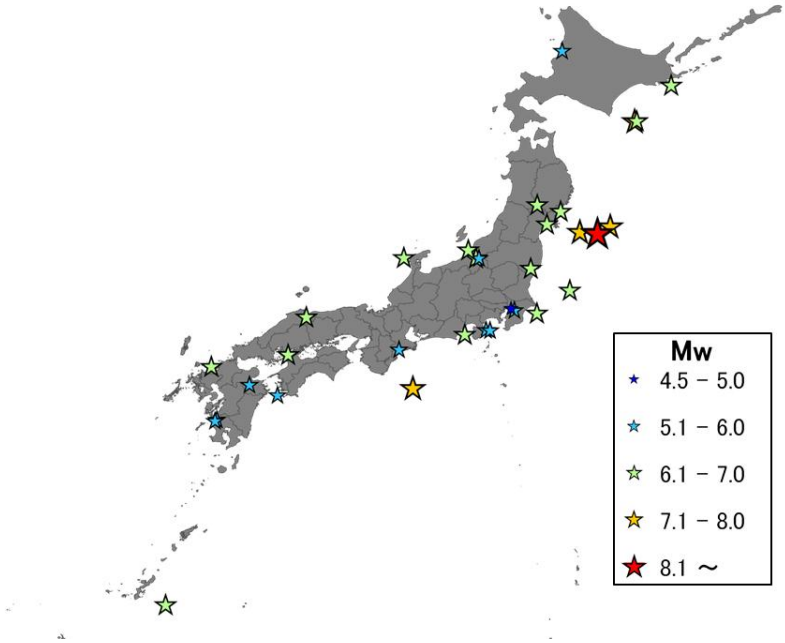

Fig. 1 Locations of epicenters for the 32 earthquake events

This study tries to develop an amplification map of response spectrum for all of Japan. To achieve this objective, the site amplification characteristics at seismic observation stations are estimated based on the attenuation relationship of its response spectrum using the K-NET (approximately 1,000 sites) and KiK-net (approximately 500 sites) ground motion records (Okada et al. 2004). The station correction factors of the attenuation relationships are used to evaluate the site amplification characteristics. To reveal the characteristics of the station correction factors, the station correction factors are compared to the site's transfer functions between the base rock and the ground surface. After obtaining the relationships between the station correction factors and the AVS30, we construct a nationwide amplification map of the velocity response spectrum.

2. ATTENUATION RELATIONSHIP OF RESPONSE SPECTRUM

We compiled the ground motion records at K-NET and KiK-net stations observed during 32 earthquake events. Figure 1 shows the epicenter locations and the moment magnitudes (Mw). The dataset consists of events that occurred from 1997 to 2011, including the 2011 Tohoku Earthquake off the Pacific coast with a Mw of 9.0. In the dataset, we have 9,734 ground motion records at 1,699 seismic observation stations. We construct the attenuation relationships for the velocity response spectrum with a damping ratio of 5%.

Eq. (1) was assumed as the attenuation relationships of response spectrum (Si and Midorikawa 2000).

$$\log_{10} y(T) = b_0(T) + b_1(T)Mw + b_2(T)r + b_3(T)\log_{10}(r + k(T)) + b_4(T)H + c_i(T) \qquad (1)$$

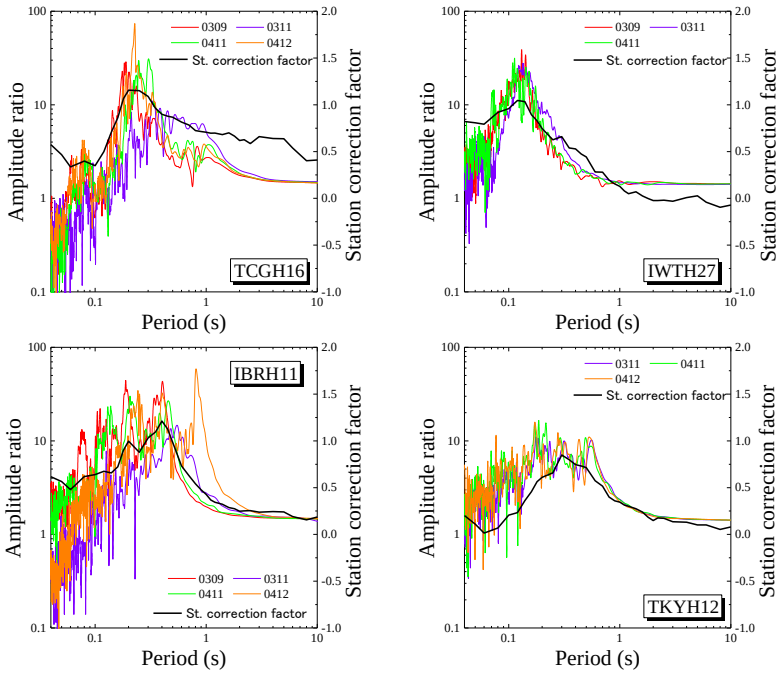

Fig. 2 Comparison between the transfer functions for several dates (colored lines) and the station correction factor (black line) at KiK-net stations

where $y(T)$ is the amplitude of the velocity response spectra with a damping ratio of 5% in cm/s. r is the shortest distance from the fault in kilometers, H is the earthquake source depth in kilometers, and the coefficients $b_i(T)$ are determined for each structural period T. The term $c_i(T)$ is the station correction factor for station i, which adjusts for site-specific amplification characteristics for a given period, assuming a mean of zero for all stations. The geometric constant b_3 was also assumed to be -1, and the coefficient $k(T)$ was modeled as

$$k(T) = k_1(T) \cdot 10^{0.5Mw} \tag{2}$$

3. COMPARISON BETWEEN THE STATION CORRECTION FACTORS AND TRANSFER FUNCTION

At each KiK-net station used in this study, the station correction factor plot was compared to the site's transfer functions. At KiK-net seismic observation stations, accelerometers are installed not only at the ground surface but also in a borehole (Okada et al. 2004). Hence, the transfer function between the base rock and the ground surface is calculated as

$$H(f) = S_{xy}(f) / S_{xx}(f) \tag{3}$$

where $S_{xx}(f)$ is the power spectrum of the acceleration at the base rock and $S_{xy}(f)$ is the cross spectrum of the acceleration between the base rock and the ground surface. We employed a smoothing technique using a Parzen window with a bandwidth of 0.2 Hz.

In the comparison with the transfer functions, the station correction factors were normalized with reference to those at rock sites. The mean of the station correction factors were calculated among 10 sites whose shear wave velocity averaged over the upper 30 m (AVS30) is larger than 1000 m/s to be used as the reference, $c_r(T)$. The station correction factors at KiK-net stations were normalized as Eq. (4), and the normalized factors are compared with the sites' transfer functions in Fig. 2.

$$c'(T) = c_i(T) - c_r(T) \tag{4}$$

In the figure, we selected the four KiK-net stations. As a whole, the plot of station correction factor versus period is similar in shape to that of the transfer functions (amplitude ratio versus period) at that site. The predominant period of the transfer function coincided with that of the station correction factors.

4. RELATIONSHIP BETWEEN THE STATION CORRECTION FACTORS AND AVS30

The discussion in the previous section indicates that the station correction factors reflect the site response characteristics. Hence, in this study we try to develop the relationships between the station correction factors and the AVS30 to define the amplification factors for a given period. Wakamatsu and Matsuoka (2013) illustrated the AVS30 distribution throughout Japan. At K-NET and KiK-net seismic observation stations, shear wave velocity profiles are also available (Okada et al. 2004). We calculated AVS30 at the seismic observation stations following the same scheme as Wakamatsu and Matsuoka (2013). We then performed a series of regression analyses between the station correction factors, $c_i(T)$ and $\log_{10}$(AVS30) for each given period (Fig. 3). In the figure, the relationships for periods of 0.5–2.5 s are illustrated, and the 95% confidence intervals are also shown.

Figure 4 shows the standard errors (Se) and correlation coefficients between station correction factors and $\log_{10}$(AVS30). When the period is longer than 0.5 s, the correlation coefficients are approximately -0.6. The standard errors are approximately 0.2 for the period of 0.5–2.5 s, and they become smaller as the periods become longer. Based on these results, we conclude that the relationships between the station correction factors for periods longer than 0.5 s and AVS30 are effective for estimating the site amplifications.

Figure 5 compares the relationships between the AVS30 and amplification factors denoted as $10^{ci(T)}$ for the periods of 0.5 and 1.0 s. The Federal Emergency Management Agency (FEMA) and the National Earthquake Hazards Reduction Program (NEHRP) aim to encourage design and building practices that address earthquake hazard and minimize the resulting risk of damage and injury. In the NEHRP Provisions (BSSC 2009), the site factors are introduced for a low-period range (F_a) and a mid-period range (F_v) in terms of the site classifications. The site classifications are defined with respect to the AVS30. We compare the NEHRP site factors with the

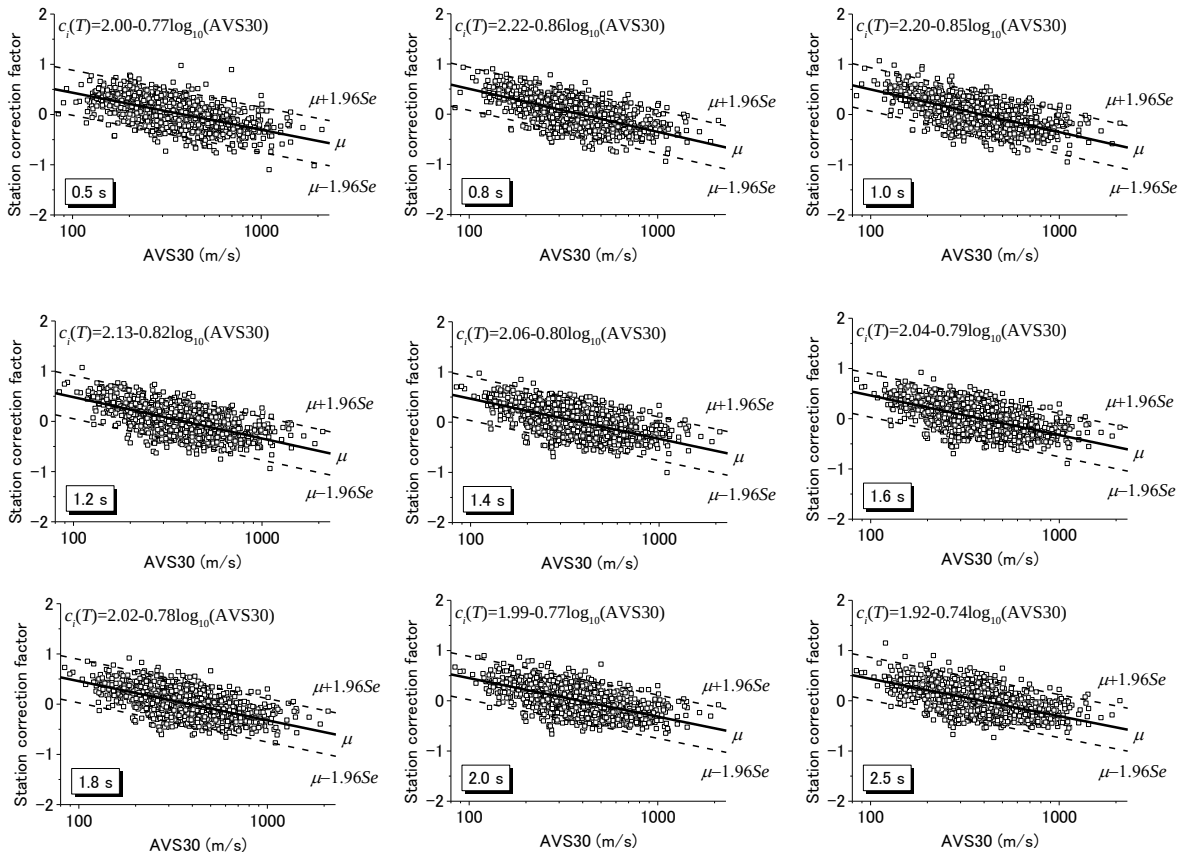

Fig. 3 Relationships between the station correction factors for a given period and AVS30

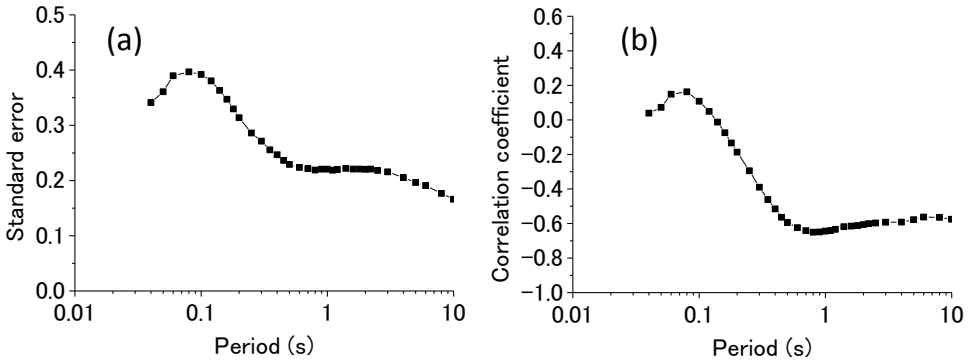

Fig. 4 (a) Standard errors and (b) correlation coefficients between the station correction factors and AVS30 with respect to the period

results of our study with the reference AVS30 of 760 m/s in Fig. 5. The effects of amplitude of input motion (S_S and S_l) are considered to show the nonlinear site amplification characteristics in the NEHRP Provisions. The amplifications estimated by our study give larger values when the AVS30 is smaller than 300 m/s for the period of 0.5 s, but are similar to the NEHRP values for the period of 1.0 s.

Choi and Stewart (2005) also developed formulas for the relationship between the amplification factors for 5% damped response spectral acceleration and the AVS30. In

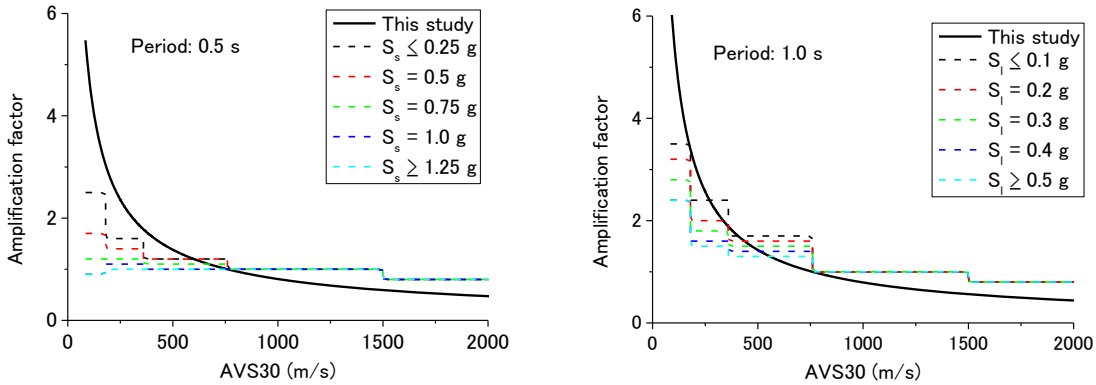

Fig. 5 Amplification factors of response spectrum for given periods by this study compared with those by the NEHRP Provisions (BSSC 2009)

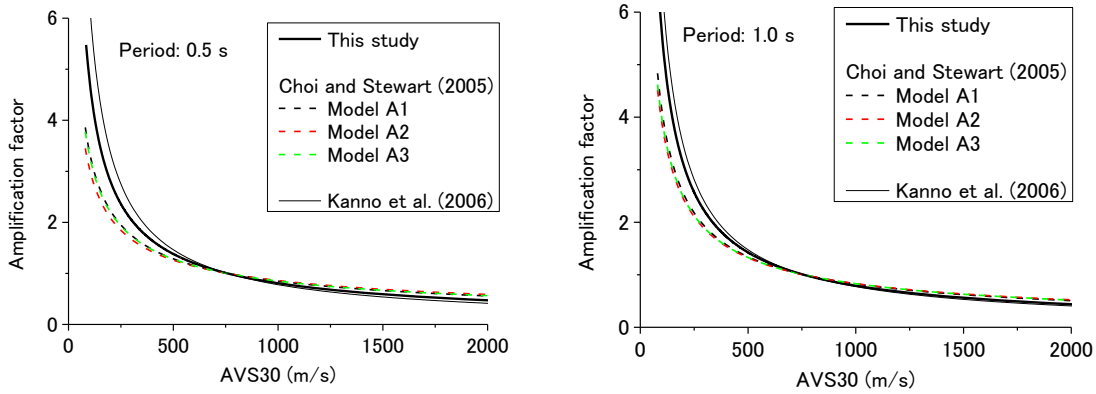

Fig. 6 Amplification factors of response spectrum for given periods by this study compared with those by Choi and Stewart (2005) and Kanno et al. (2006)

their study, the ground motion records obtained in the U.S. and Turkey were employed. Assuming the reference AVS30 of 760 m/s, we compare the formulas developed by Choi and Stewart (2005) with the results of this study in Fig. 6. Kanno et al. (2006) considered the site effects as a correction term of the attenuation relationship to improve the accuracy of estimation of ground motion. They developed a formula similar to the one proposed by Choi and Stewart (2005), by including the ground motion records obtained in Japan. Kanno et al.'s (2006) formula is also illustrated in Fig. 6, and all the relationships are normalized with the reference AVS30 of 760 m/s. No significant differences are observed when the AVS30 is larger than 500 m/s. The amplification factors estimated by this study fall between those estimated using the formulas developed by Choi and Stewart (2005) and Kanno et al. (2006). Based on these facts, the station correction factors are applicable for estimating the periodic site amplifications.

Employing the distribution of AVS30 throughout Japan developed by Wakamatsu and Matsuoka (2013) and the relationships between the station correction factors and AVS30 shown in Fig. 3, we estimated the amplification factors of the response velocity spectrum with respect to the reference layer with the shear wave velocity of 600 m/s

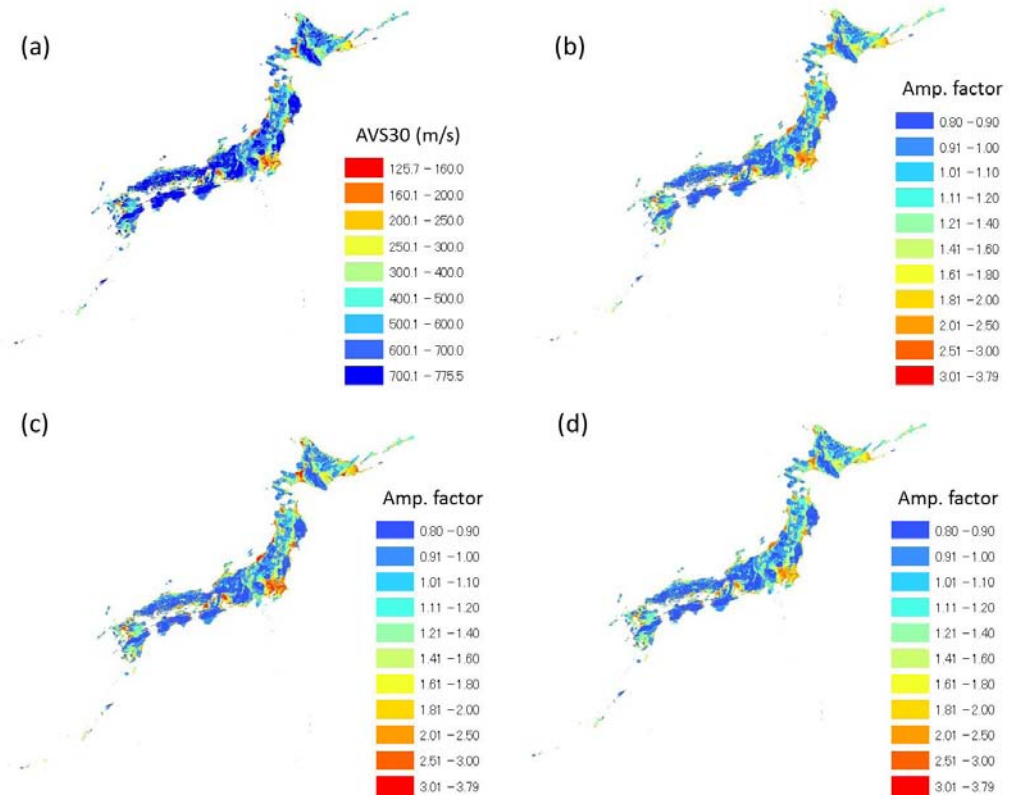

Fig. 7 (a) Distribution of AVS30 throughout Japan developed by Wakamatsu and Matsuoka (2013), and amplification factors of velocity response spectrum with respect to the reference layer with the shear wave velocity of 600 m/s for periods of (b) 0.5 s, (c) 1.0 s, and (d) 2.5 s

shown in Fig. 7. The response spectrum with the period of 1.0 s is much amplified in the middle of the region and in the area along Tokyo Bay.

5. CONCLUSIONS

In this study, we investigated how to estimate the site response characteristics using the station correction factors of attenuation relationships for the response spectrum. To this end, 9,734 ground motion records at 1,699 seismic observation stations during 32 earthquake events were employed, and the attenuation relationships for the velocity response spectrum with a damping ratio of 5% were constructed. We obtained station correction factors for the 1,699 seismic observation stations, and evaluated them with respect to the shear wave velocity averaged over the upper 30 m (AVS30).

The station correction factors could be applicable in estimating periodic site amplifications. Lastly, we constructed a map showing the nationwide distributions of amplification factors of response spectrum for specific periods. The periodic contents of ground shaking can be estimated using these amplification maps. In future studies, the nonlinear effects of surface soil need to be properly treated.

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