Estimates of Spectral Acceleration Amplification of Observation Stations in the Iwate-Miyagi and Niigata Regions, Japan

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LISBOA 2012

SUMMARY:
We estimated empirical amplification factors for seismic stations in the Iwate-Miyagi and Niigata regions, Japan for period ranges of 0.05–5 s. We adopted the method of Si et al. (2010) in which the empirical amplification factors are estimated by averaging ratios of observed and predicted ground motions using reference ground motion attenuation models (GMPEs). The model of Kanno et al. (2006) was used to estimate the 5%-damped acceleration spectra on the bedrock. The results show large amplification at periods of 0.1 s or shorter at stations located in mountainous area and it is reduced for longer periods. However, at stations located on basins, large amplification is found at long periods of 1–5 s. The tendency of our results agrees well with theoretical transfer functions. The method is efficient to calculate site effect at observation stations where imperfect velocity structure is available.

Keywords: Amplification factor, spectral acceleration, empirical amplification factor

1. INTRODUCTION

Evaluation of site effect is very important in the prediction of strong motions based on empirical ground motion prediction equations (GMPEs). Some studies adopted the average shear-wave velocity of top 30 m (AVS30) as a correlated factor to the site amplification (Borcherdt et al., 1991; Midorikawa et al., 1994; Kanno et al. 2006; NGA project, 2008). However, AVS30 appears not the only parameter controls the site amplification factor. For instance, Anderson et al. (1996) studied the effect of surficial geology on the ground motions. They examined numerical results for both simple and very irregular 1-D velocity models. They found that the character of the seismogram and the peak spectral frequencies, are strongly influenced not only by the thickness but also by the intervening layers. Castellro et al. (2008) and Lee and Trifunac (2010) emphasized that AVS30 should not be the only site parameter used to scale strong motion amplitudes. In addition, this approach is not applicable if the sub-structural information is not available at the target site.

Zhao et al. (2006) classified the site effects for seismic stations in Japan based on the spectral ratio of H/V of earthquake records. The basic assumption of this method is that the local geology only influences the horizontal components of seismic waves, but not the vertical one. Then site response is obtained by dividing the spectral amplitudes of the horizontal component to the vertical component at the same site. In a previous study, Riepl et al. (1998) found that the method is sensitive to possible phase interactions and phase conversions due to local heterogeneities which could amplify the vertical component of the ground motion by almost the same order of magnitude as the horizontal components.

Recently, Si et al. (2010) proposed a simple method to investigate the site effects by means of summing up ratios of observed and predicted ground motion. Their method showed good results when tested for data from four regions in Japan (e.g., Si et al., 2011). We implemented correction for peak ground velocities (PGVs) estimated using ground motion attenuation model of Si and Midorikawa (1999). It is also convenient for its usage, especially when the sub-structural information is not available at the observation point.

In this study, we extended the method of Si et al. (2010) to find 5%-damped acceleration response spectral amplification factors (empirical amplification factors, hereinafter) of 0.05–5 s for the Iwate-Miyagi and Niigata regions. The empirical amplification factors of spectral accelerations were used to correct for the observed strong motion data of two crustal earthquakes; the 2008 Iwate-Miyagi Nairiku earthquake (M_w 6.9) and the 2004 Niigata-ken Chuetsu earthquake (M_w 6.6) in Figure 1. We also corrected the same database using the site correction relation of Kanno et al. (2006). Finally, we did a comparison between the corrected databases to validate the adopted method.

2. METHOD

Si et al. (2010) estimated the site effect by averaging of the observed and the predicted strong ground motions. Their relation is expressed as:

$$R(\omega) = \left(\sum_{i=1}^{n} \left(O(\omega)/O^{'}(\omega) \right) \right)^{1/n} = \left(\sum_{i=1}^{n} \left(G(\omega)/G^{'}(\omega) \right) + \varepsilon_i \right)^{1/n} \tag{2.1}$$

where, $R(\omega)$ is the empirical amplification factor, index i represents earthquake record, n is the total number of records used for site effect estimation for each station, $O(\omega)$ is the root mean square of the two maximum horizontal components. $O'(\omega)$ is the predicted ground motion using a reference ground motion attenuation model (GMPEs) defined on the bedrock, $G(\omega)$ is the site effect on the ground surface, $G^{'}(\omega)$ is the site effect on the bedrock, and ε_i is a random number, which decreases with an increase in the number of observations as examined by Si et al. (2011).
We used the model of Kanno et al. (2006) for shallow events where focal depth is less or equal to 30 km to estimate the 5%-damped acceleration response spectra (Eq. 2.2). The bedrock is defined for average shear wave velocity (AVS30) of 300 m/s. The relation is expressed as:

$$\log pre = a_1 M_w + b_1 X - \log(X + d_1 10^{e_1 M_w}) + c_1 \tag{2.2}$$

where pre is the 5%-damped acceleration response spectra (cm/s^2). M_w is the moment magnitude, X is the fault distance (km), it refers to the hypocentral distance because we just use small earthquakes in our study. e_1 = 0.5 for all the periods. a_1, b_1, d_1, and c_1 are regression coefficients defined at 37 periods between 0.5–5 s by Kanno et al. (2006).

3. STRONG MOTION DATA

The selection criteria which we adopted in this study were as follows,

1- Moment magnitude M_w is between 4.0 and 6.0, we just chose small earthquakes in order to avoid any nonlinear effect, which could possibly occur at the observation stations.
2- Hypocentral distance is less than 50 km to minimize of the path effect.
3- We only chose the crustal events with focal depth less than 30 km.
4- Maximum PGA exceeds 10 cm/s^2 for records with good signal-to-noise ratio.
5- Number of records for each station is greater than or equal to 5. Increasing the number of events might also minimize the path effect.

We selected data from two seismically active regions in Japan. The first one is the Tohoku region to the north-eastern part of the Honshu Island. The other one is the Niigata region to the western part of the Honshu Island. We located 87 and 79 earthquakes between 1997 and 2011 in the Tohoku and Niigata regions, respectively. Number of the stations which satisfied the selection criteria was 38 and 37 for the Tohoku and Niigata regions, respectively. We used the two horizontal components of the strong motion records from K-NET and KiK-net operated by the National Institute for Earth Science and Disaster Prevention (NIED). Most of the selected stations in the Tohoku region are located in the Iwate and Miyagi prefectures. The study area has been strongly affected by many large earthquakes, such as the 2008 Iwate-Miyagi Nairiku (M_w 6.9) and the 2011 Tohoku earthquake (M_w 9.1). The selected stations in the Niigata regions are close to the source area of the 2004 Niigata-ken Chuetsu earthquake (M_w 6.6). The earthquake data and selected stations are presented in Figure 2. A high-pass filter of 0.1 Hz was applied to eliminate the long-period ground motions from whole recorded data.

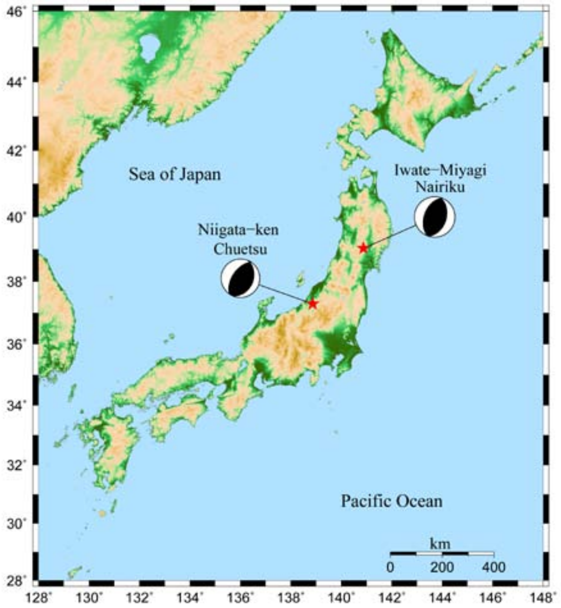

Figure 1. Map showing the epicenters of the 2008 Iwate-Miyagi Nairiku and 2004 Niigata-ken Chuetsu earthquakes (red stars). The focal mechanisms of both earthquakes are according to the Global CMT solutions.

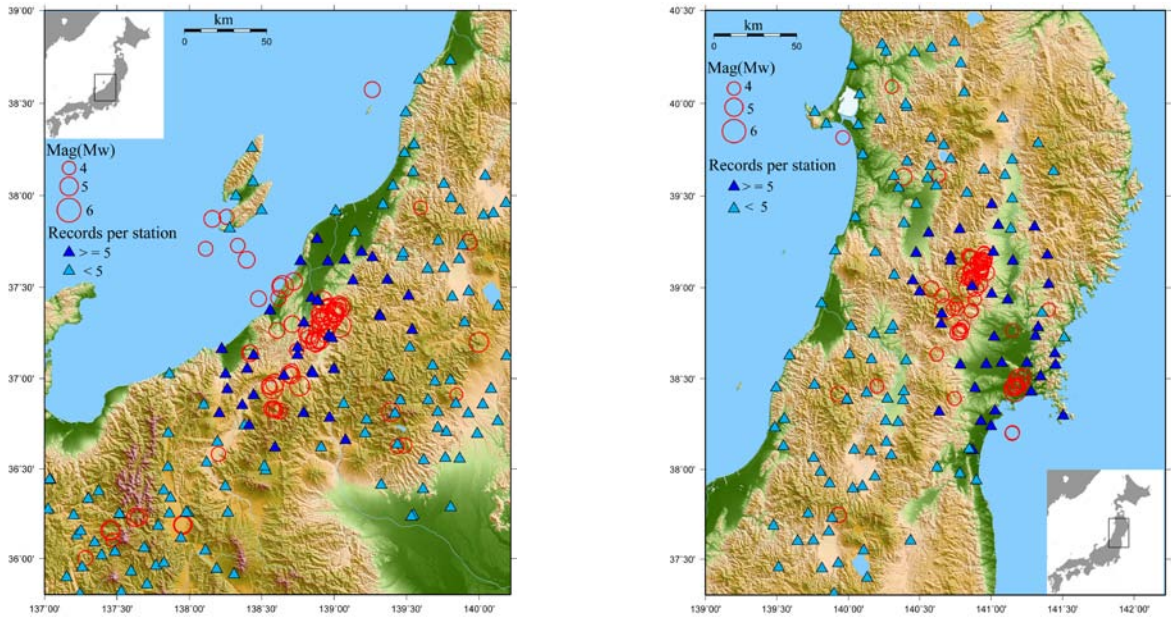

Figure 2. Left and right panels respectively showing the topography map of the Niigata and Tohoku regions, with earthquakes distribution (red circles). Light blue triangles indicate stations recording less than 5 earthquakes. Dark blue triangles indicate stations recording ≥ 5 earthquakes, which were used in this study.

4. RESULTS AND DISCUSSION

We found the spectral acceleration empirical amplification factors for the studied areas at periods of 0.05 to 5 s. Among the broad range of investigated periods we show six periods from the viewpoint of engineering interest, the chosen periods are 0.1, 0.3, 0.5, 1, 2, and 5 s. Figures 3 and 4 show the spatial distribution of the empirical amplification factors for the aforementioned periods. Large amplification was dominated at most stations in both studied areas at periods of 0.1 s and shorter. The borehole data from K-NET and KiK-net reveal that most stations are dominated by a very soft shallow layer at the free surface of about 5–10 m. The velocity contrast with the free surface could be the reason of such large amplification. For instance, MYG002 station has a shear-wave velocity of 590 m/s at 7 m depth which decrease to 400 m/s. *S*-wave velocity decreases again to 270 m/s at depth of 5 m, and it is also decrease to 140 m/s at 1 m depth. For periods of 0.5 s and longer, the amplification is still large in the most stations located in the basin and the coastal areas. De-amplification is dominated for stations located in the mountainous areas at periods of 0.5 to 5 s such as AKTH06, IWT025, IWTH22, and so on in the Iwate-Miyagi regions, it is also noticed for the Niigata regions for stations such as NIGH19, GNM002, FKS030, and so on. Those stations are located on hard rock sites where the shear-wave velocity could reach more than 600 m/s after the shallow soft layer we previously mentioned.

We compared our results to that by Tsuda et al. (2006), who studied the site effect for the Iwate-Miyagi area using the aftershock data of the 2005 Miyagi-oki earthquake. They applied a spectral inversion technique of the dataset to separate the source, path, and site effects. Same tendency were shown by both studies, but the amplification factors were slightly different. At the station MYG005, large amplification was found at long-periods of 2–5 s. The site is located on a caldera surrounded by mountains with a deep basin of 0.9 km. Our results were in good agreement with long-period amplification observed by Motoki et al. (2010), who conducted a microtremor measurement around MYG005. They concluded that the site amplification is affected not only by 1-D velocity structure but also by the effect of irregular velocity structure of 4 km in the surrounding area. For comparison, we also calculated the theoretical transfer functions by SHAKE91 for stations with AVS30 close to 300 m/s. 6 stations were selected from the studied areas such as AKTH19, IWTH20, MYGH05, IWTH26, NIGH11, and FKSH21 which have AVS30 of 287, 288, 305, 371, 375, and 365 m/s, respectively. Our results were almost similar to those obtained from the theoretical transfer functions for short periods of less than 1 s. However, our results for long periods (more than 1 s) could not be compared with those of the theoretical transfer functions, because we used shallow layers up to 30 m to calculate transfer functions (Figure 7).

We used our empirical amplification factors to get the acceleration spectra at the bedrock for periods of 0.1, 0.3, 0.5, 1, 2, and 5 s, for the 2008 Iwate-Miyagi Nairiku and 2004 Niigata-ken Chuetsu earthquakes. The site correction relationship of Kanno et al. (2006) was also used to get for acceleration spectral values at the bedrock as expressed in the following equation,

$$O_b(\omega) = O_s(\omega) / R(\omega) \tag{4.1}$$

where, $O_b(\omega)$ is the 5%-damped acceleration spectra on bedrock, $O_s(\omega)$ is the original observed 5%-damped acceleration spectra on the free surface, $R(\omega)$ is either the empirical amplification factor proposed by this study or the site effect correction factor calculated according to Kanno et al. (2006).
The corrected data by our empirical amplification factors fit better with GMPEs. To check the validity of our analysis, we carried out error analyses by estimating the residual and the standard deviation before and after corrections. We found that both residual and standard deviation were reduced after correction, as shown in Figures 5 and 6. The standard deviation values of the 2008 Iwate-Miyagi Nairiku and 2004 Niigata-ken Chuetsu earthquakes with respect to the assigned periods are shown in Tables 4.1 and 4.2.

Table 4.1. The Standard Deviation Values of the 2008 Iwate-Miyagi Nairiku Earthquake

Period / Std.	0.1 s	0.3 s	0.5 s	1 s	2 s	5 s
Obs/Pre	0.26	0.30	0.33	0.43	0.36	0.28
Obs_{cor_K06}/Pre	0.23	0.35	0.40	0.50	0.40	0.33
$Obs_{cor\_this\ study}$ /Pre	0.16	0.19	0.20	0.26	0.23	0.19

Table 4.2. The Standard Deviation Values of the 2004 Niigata-ken Chuetsu Earthquake

Period / Std.	0.1 s	0.3 s	0.5 s	1 s	2 s	5 s
Obs/Pre	0.26	0.28	0.33	0.36	0.36	0.27
Obs_{cor_K06}/Pre	0.28	0.31	0.30	0.33	0.31	0.23
$Obs_{cor\_this\ study}$ /Pre	0.22	0.25	0.19	0.21	0.20	0.13

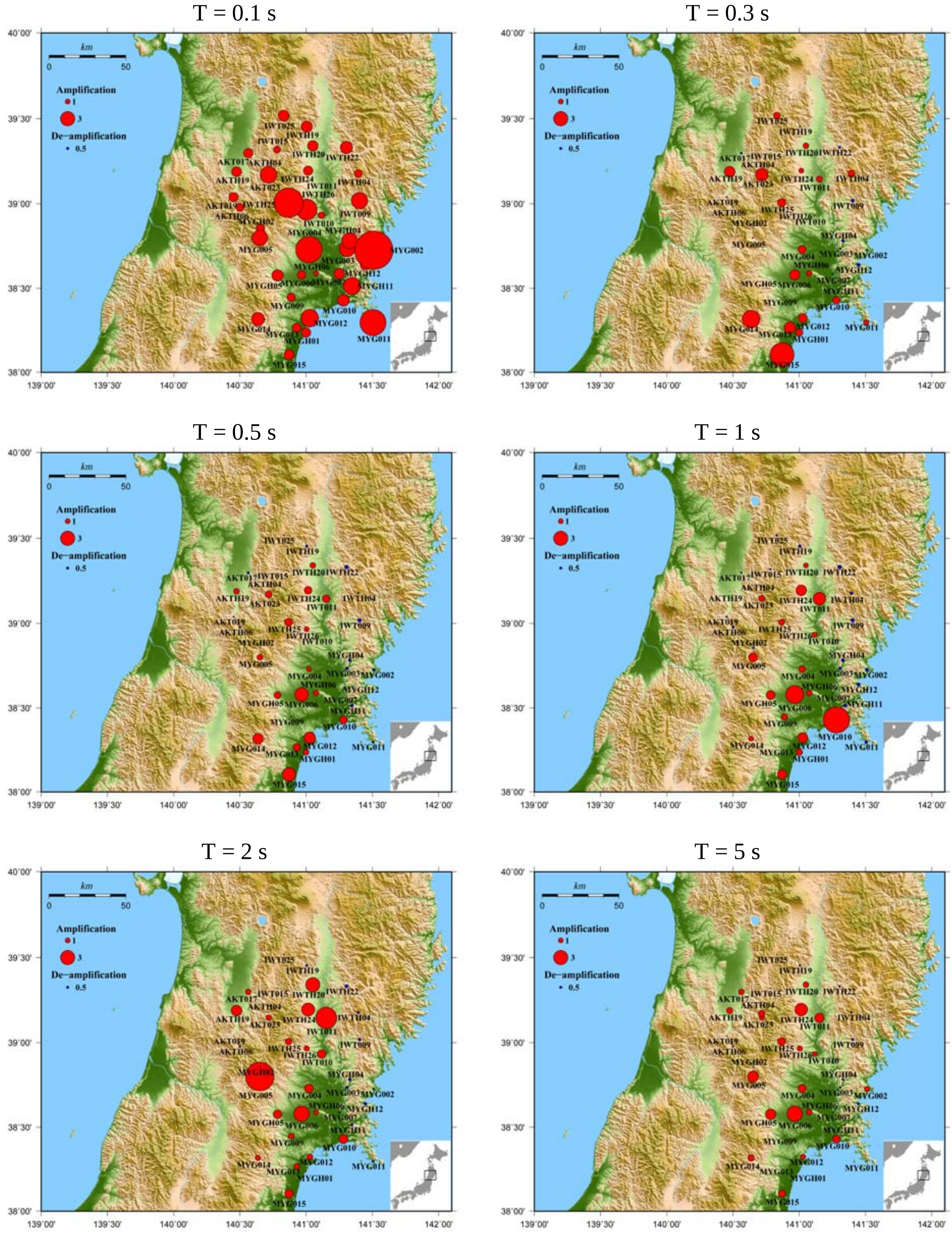

Figure 3. Maps showing the empirical amplification factors of spectral accelerations at periods of 0.1, 0.3, 0.5, 1, 2, and 5 s in the Iwate-Miyagi region. Large amplification is dominated at most stations at short period of 0.1 s. For periods of 0.5 s and longer, large amplification is dominated at most stations located in the basin and coastal areas.

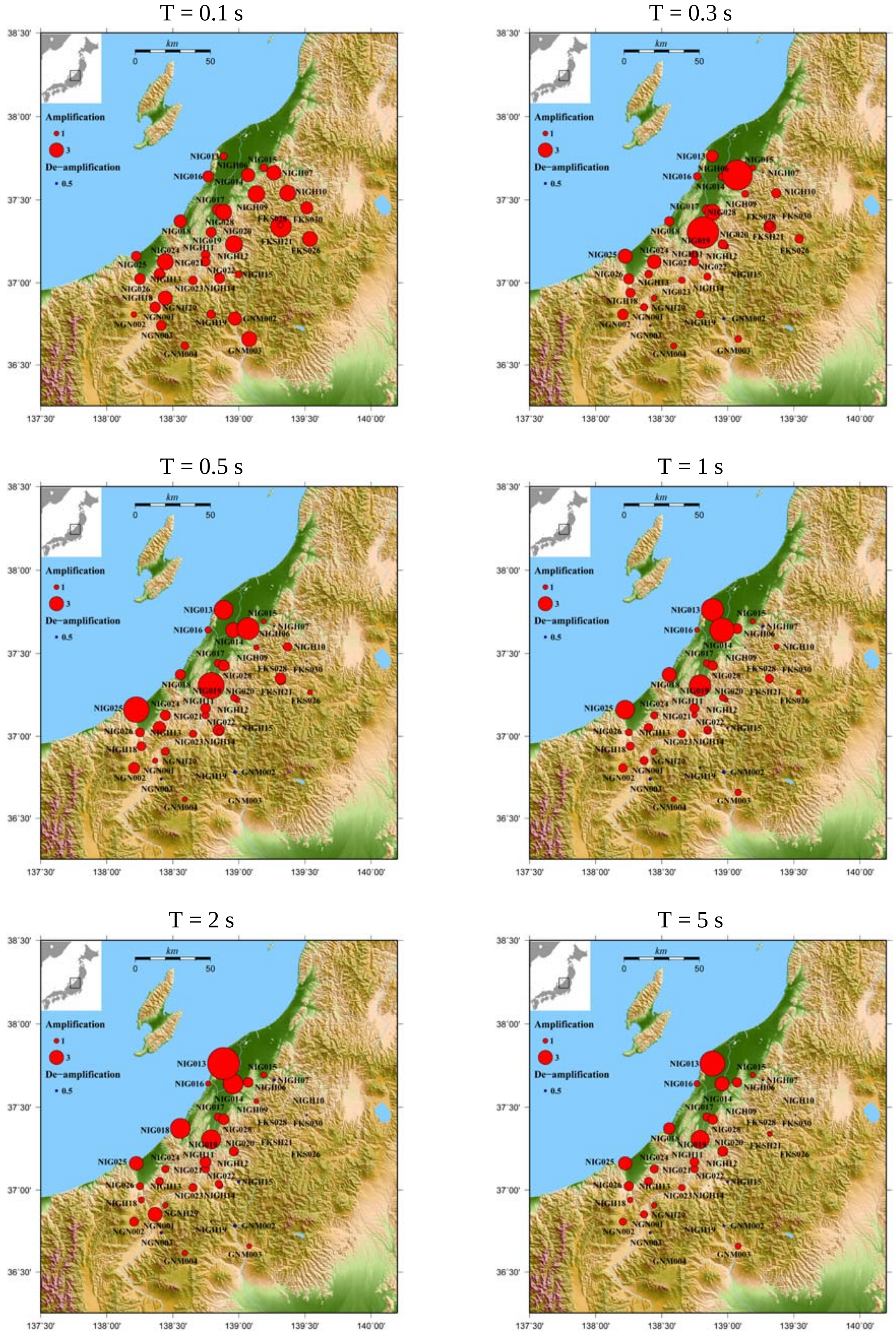

Figure 4. Maps showing the empirical amplification factors of spectral accelerations at periods of 0.1, 0.3, 0.5, 1, 2, and 5 s in the Niigata region. Large amplification is dominated at most stations at short period of 0.1 s. For periods of 0.5 s and longer, large amplification is dominated at most stations located in the basin and coastal areas.

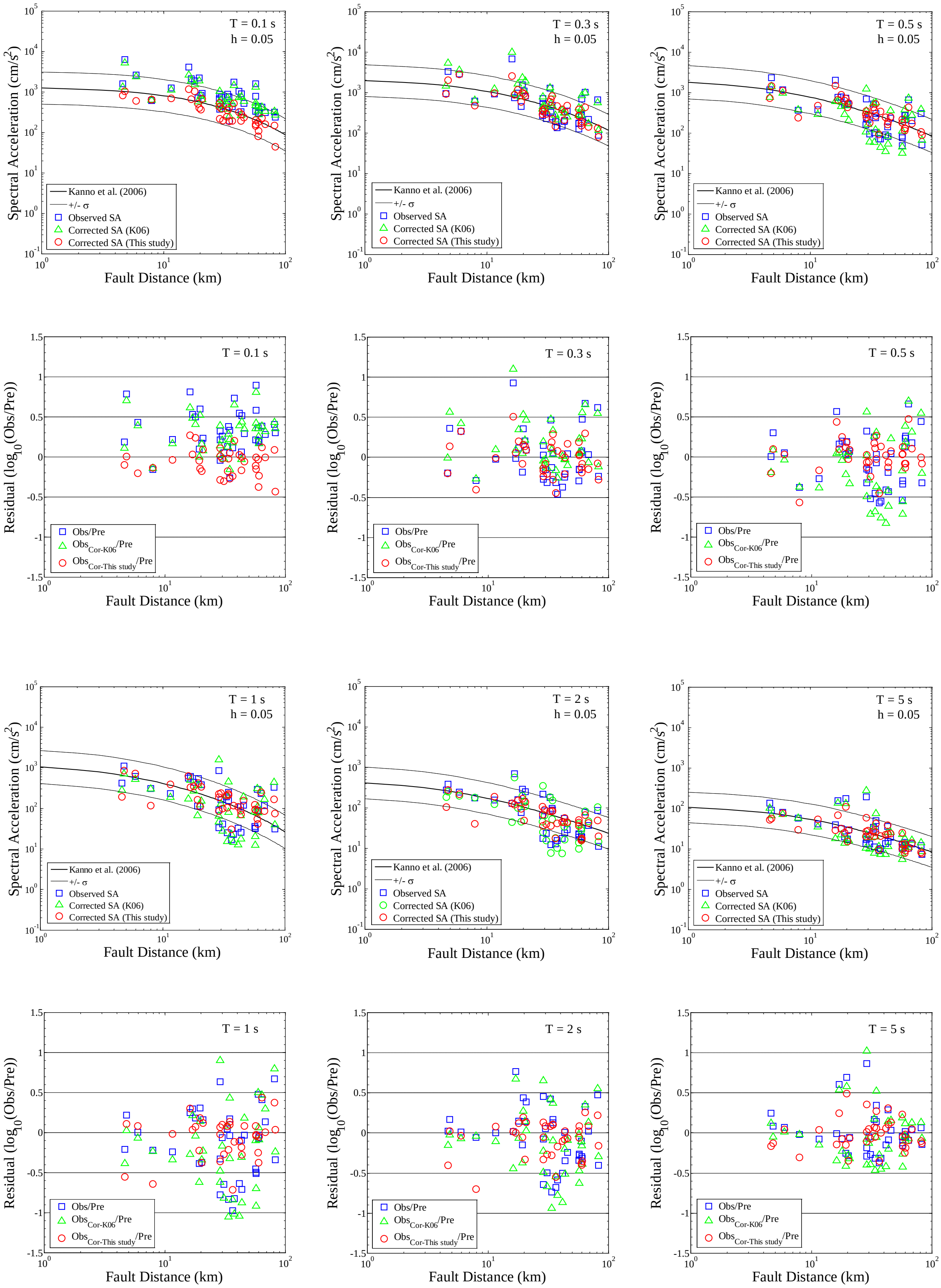

Figure 5. Showing the distribution of the acceleration spectra of the 2008 Iwate-Miyagi Nairiku earthquake with attenuation relationship of Kanno et al. (2006) at periods of 0.1, 0.3, 0.5, 1, 2, and 5 s. We also show the corrected acceleration spectra by using our empirical amplification factors and the correction factors according to the relation of Kanno et al. (2006) (upper panels). Lower panels show the residual distribution at the same periods of the original and corrected acceleration spectra to the predicted ones by Kanno et al. (2006).

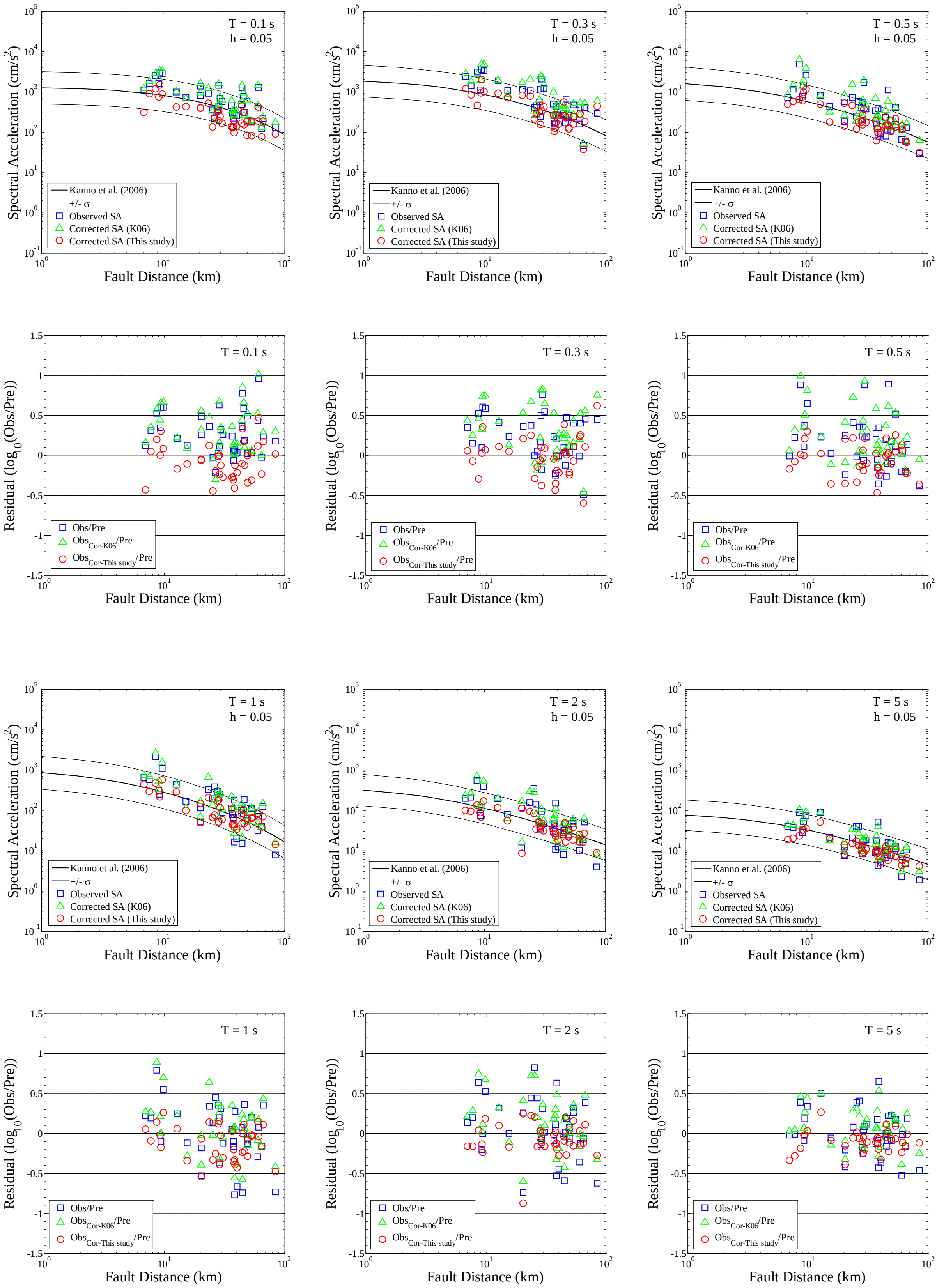

Figure 6. Showing the distribution of the acceleration spectra of the 2004 Niigata-ken Chuetsu earthquake with attenuation relationship of Kanno et al. (2006) at periods of 0.1, 0.3, 0.5, 1, 2, and 5 s. We also show the corrected acceleration spectra by using our empirical amplification factors and the correction factors according to the relation of Kanno et al. (2006) (upper panels). Lower panels show the residual distribution at the same periods of the original and corrected acceleration spectra to the predicted ones by Kanno et al. (2006).

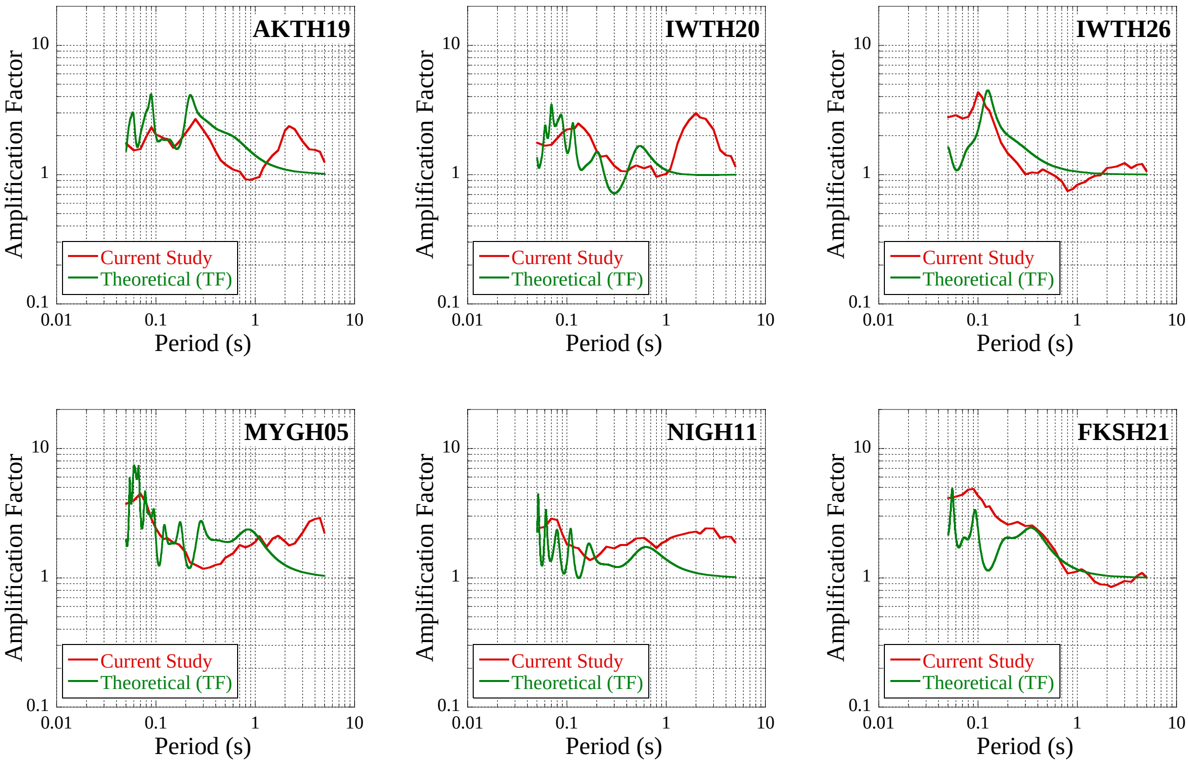

Figure 7. Comparison between the empirical amplification factors of this study and the theoretical transfer functions calculated by SHAKE91. Close trend is shown at short period range less than 1 s.

5. CONCLUSIONS

We calculated the empirical amplification factors of spectral accelerations for the Iwate-Miyagi and Niigata regions in Japan by adopting the method of Si et al. (2010). The proposed method is useful to estimate the site amplification factors for seismic stations, where imperfect sub-structural information is available. The site amplification factors obtained by this study and that by using the theoretical transfer functions are in good agreement in frequency dependency at short periods. We applied the correction factors for the strong motion records of the 2008 Iwate-Miyagi Nairiku and 2004 Niigata-ken Chuetsu earthquakes. The corrected ground motions fit better with the prediction by GMPEs comparing to the site correction relationship of Kanno et al. (2006).

AKCNOWLEDGEMENT

K-NET/KiK-net strong motion data used in this study were provided by the National Institute of Earth Science and Disaster Prevention (NIED).

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