Correction of Ground Motion Prediction Equation Using Aftershock Observation Records of The 2011 off the Pacific Coast of Tohoku Earthquake

N. Tsutsumi, T. Itoi & T. Takada
the University of Tokyo, Japan

15 WCEE
LISBOA 2012

SUMUMMARY:
Since Kobe earthquake in 1995, ground motion observation network has been developed all over Japan. Thanks to the network, dense strong motion records were obtained during Tohoku Earthquake (M_w 9.0) including many aftershocks. In this paper, we analyze the observed records due to these aftershocks, and propose a correction methodology of ground motion prediction equation, which is expected to be used for prediction of ground motions due to future main shocks. Aftershocks with magnitude 5.0 and larger are selected. Firstly, we calculate residuals of the observed records from an existing ground motion prediction equation, and then evaluate the site amplification characteristics as a residual. Then, we examine the characteristics of residual, and construct a model between epicenter locations and residuals. Based on the results of the above corrections, we propose a highly accurate prediction model for this region. Finally, we verify this model with observed records of large historical earthquakes.

Keywords: Ground motion prediction equation, Aftershock records, Prediction accuracy, Residual

1. INTRODUCTION

Various ground motion prediction equations of Japan are proposed by regression analysis of ground motions various ground motion characteristics recorded at different observation stations. Anderson & Uchiyama (2011) pointed out that the propagation characteristic of ground motion increases the uncertainty of the ground motion prediction equation. Though it is recommended that coefficients of ground motion prediction equations should be obtained specific to each region, it is difficult because of insufficient number of data. Furthermore, the effect of source characteristics such as fault type has also been pointed out. Extracting its effect is difficult, because of the following two reasons; one is a large variation of predicted results, another is shortage of seismic motion records those fault type are different.

Thousands of aftershocks occurred within half a year after the 2011 off the Pacific Coast of Tohoku Earthquake (Tohoku earthquake) in quite wide subduction zones of an epicentral region of the main shock, and sufficient number of strong motion records were observed at hundreds of K-NET stations in Tohoku region. These records should be fully utilized for incorporating effects of site, path and source mechanisms to the existing ground motion prediction.

In this paper, aftershock records of Tohoku Earthquake obtained by dense ground motion observation network are utilized. Focusing on site characteristics and relationship between the site and epicenter locations, the methodology to correct an existing ground motion prediction equation is proposed, to sophisticate the ground motion prediction of future main shocks occurring in Tohoku region.

2. CORRECTION OF GROUND MOTION PREDICTION EQUATION CONSIDERING THE EPICENTER LOCATION AND SITE CHARACTERISTICS

By calculating the residual of observed ground motions due to aftershocks from predicted one by equations of PGA (peak ground acceleration), PGV (peak ground velocity) and Sa (acceleration response spectrum), gives us a correction factor reflecting site characteristics and epicentre characteristics.

Based on segmentation for probabilistic seismic hazard analysis by National Research Institute for Earth Science and Disaster Prevention, A correction method for ground motion prediction equation is proposed in the region shown in Figure 2.1. Aftershocks ($M_J >= 5.0$) are selected which occurred in and around this region. In this study, $M_j = M_w$ is assumed. Ground motion acceleration records are recorded at K-NET MYG001 (Kesennuma), MYG010 (Ishinomaki) and MYG013 (Sendai) used. Those observation points are close to the source region of Tohoku Earthquake. Epicenter latitude, longitude and depth, magnitude are compiled from the JMA hypo chart list. The epicenter locations of aftershocks and the observation point positions are shown in Figure 2.1.

First, “site correction factor” is obtained focusing on each observation point. Residuals of the aftershock records from the predicted value (PGA or PGV or Sa) is calculated by the formula (2.1) as follows:

$$\delta_{ij} = \ln(R_{ij}^{o}) - \ln(R_{ij}^{p}) \tag{2.1}$$

R_{ij}^{o} is the observed ground motion. R_{ij}^{p} is calculated using a ground motion prediction equation by Kanno *et al.* (2005) as follows:

$$\log_{10} R_{ij}^{p} = aM_w + bX - \log_{10} X + c + \log_{10} G_j \tag{2.2}$$

Where X (km) is the shortest fault distance. a, b and c are regression coefficients. Two ground motion prediction equations are proposed by *Kanno et al. (2005)*: one is for a shallow earthquakes, the other is for deeper earthquakes. In this paper, the former equation (Equation 2.2) is used for all earthquakes. To calculate the shortest fault distance X, a fault length is assumed to be obtained by a sphere whose diameter is calculated by Equation 2.3 (Utsu, 1997) as follows:

$$\log_{10} L = 0.5M_w - 1.85 \tag{2.3}$$

The shortest distance X is calculated as distance from observation point to hypocenter subtracted by $1/2\,L$. G_j is a site amplification factor, depending on average shear wave velocity $AVS30$ at each observation point as follows:

$$\log_{10} G_j = p \log_{10} AVS30 + q \tag{2.4}$$

$$AVS20 = \frac{20}{\sum (H_h / V_{Sh})} \tag{2.5}$$

$$AVS30 = 1.13AVS20 + 19.5 \tag{2.6}$$

H_h is the thickness of the hth layer. V_{Sh} is the S-wave velocity of the hth layer. p and q are regression coefficients. If soil structure up to 20 meter depth is not obtained, the S-wave velocity of the bottom layer would assume to continue up to 20m depth. R_{ij}^{o} (PGA, PGV and Sa) is calculated as sum of square of two horizontal components in the time domain as follows: b

$$R_{ij}^{o} = \max\sqrt{{R_{EW}}^{2} + {R_{NS}}^{2}} \qquad (2.7)$$

Mean residual is calculated by the following equation to obtain the site correction term δ_j^{I} at observation point j. n is the number of aftershocks of the observation point j.

$$\delta_j^{\mathrm{I}} = \frac{1}{n}\sum_{i=1}^{n}\delta_{ij} \qquad (2.8)$$

Second, "epicenter location correction term" corresponding to each epicenter latitude, longitude and depth is determined. Residuals of the aftershock records and predicted values after the site correction $\delta_{ij}^{\mathrm{II}}$ are obtained as follows:

$$\delta_{ij}^{\mathrm{II}} = \ln(R_{ij}^{o}) - \ln(R_{ij}^{p}) - \delta_j^{\mathrm{I}} \qquad (2.9)$$

Based on $\delta_{ij}^{\mathrm{II}}$ obtained from aftershocks, spatial distribution of epicenter location correction term are obtained by spatial interpolation of each 0.025 degree of latitude and longitude and each 1.0 km of depth. The interpolated epicenter location correction term is employed for the historical (or future) earthquake (called the *k*-th earthquake in the following part).

Indicators are introduced in order to examine the effect of the corrections. Predicted ground motion by existing ground motion prediction equation is represented as R_{kj}^{p} of the *k*-th earthquake at the *j*-th observation point. $R_{kj}^{p\mathrm{II}}$ is the predicted after site correction and $R_{kj}^{p\mathrm{III}}$ is the predicted after the site correction and the epicentre location correction.

$$\ln(R_{kj}^{p\mathrm{II}}) = \ln(R_{kj}^{p}) + \delta_j^{\mathrm{I}} \qquad (2.10)$$

$$\ln(R_{kj}^{p\mathrm{III}}) = \ln(R_{kj}^{p}) + \delta_j^{\mathrm{I}} + \delta_{kj}^{\mathrm{II}} \qquad (2.11)$$

Residuals of the ground motions are calculated as in the case of aftershocks. A new symbol ε_{kj}^{l} is used instead of δ_j^{l} to distinguish it from aftershocks. In Equations 2.12 and 2.13, $l = \mathrm{I}, \mathrm{II}, \mathrm{III}$. Standard deviation of the residuals shown in Equation 2.13 is used asthe indicator of prediction accuracy. N is the total number of all observed ground motions at all observation points.

$$\varepsilon_{kj}^{l} = \ln(R_{kj}^{o}) - \ln(R_{kj}^{pl}) \qquad (2.12)$$

$$\sigma^{l} = \sqrt{\frac{1}{N}\sum_{k,j}(\varepsilon_{kj}^{l})^{2}} \qquad (2.13)$$

The standard deviation of residuals of aftershocks used for producing correction term and for the past earthquakes are compared (hereafter called test earthquakes). Test earthquakes is earthquakes which occurred around the region in Figure 2.1 and its magnitude M_w is larger than 5.0. Its epicentre locations are shown in Figure 2.1.

Table 2.1 shows the standard deviations of PGA and PGV residuals which correct aftershocks itself. Table 2.2 shows the case for test earthquakes. In Table 2.1 standard deviations decrease as correction terms are added. The accuracy can be improved. On the other hand, standard deviations tend to increase as correction process proceeds as shown in Table 2.2. From this result, it is considered that correction terms obtained from aftershocks cannot be applied directly to the historical earthquakes.

Figure 2.2 shows the standard deviations of residuals for Sa which correct aftershocks itself. Figure

2.3 shows the case which corrects test earthquakes. In Figure 2.2 standard deviations decrease as correction process proceeds. This is consistent with the case of PGA and PGV. On the other hand, the standard deviation decreases only at the longer period (T>0.6s) if site correction applied for test earthquakes. Standard deviation increases at shortter period. One of the reasons isconsidered due to non-linearity of the surface soil characteristicsIncrease in standard deviation of PGA and PGV is considered due to the same reason as increase in Sa at shorter period. Significant improvement in accuracy is not observed in epicenter location correction. This tendency is very different from the correction for aftershocks itself. One of reasons that correction by the spatial interpolation is not a valid is considered because focal mechanism is different even those epicenter locations are close to each other.

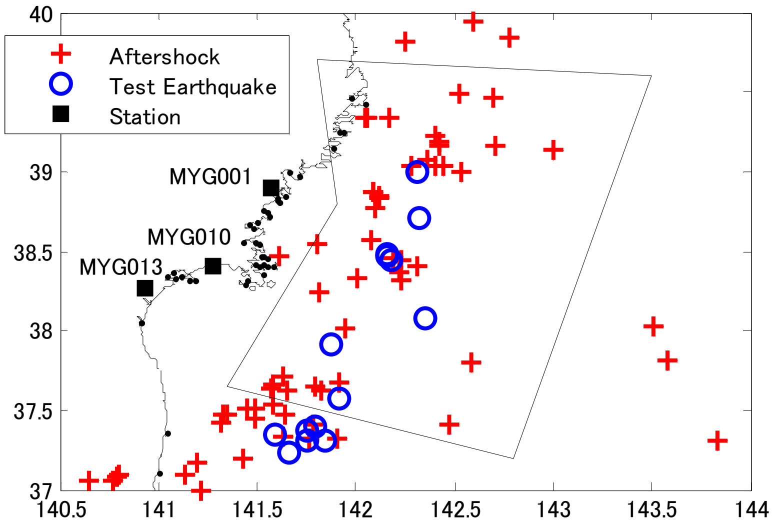

Figure 2.1. Epicenters of Aftershocks and Test earthquakes

Table 2.1. Standard Deviation of PGA and PGV of the Aftershocks

	σ^{I}	σ^{II}	σ^{III}
PGA	0.73	0.57	0.06
PGV	0.61	0.58	0.05

Table 2.2. Standard Deviation of PGA and PGV of the Test Earthquakes

	σ^{I}	σ^{II}	σ^{III}
PGA	0.58	0.72	0.84
PGV	0.63	0.71	0.79

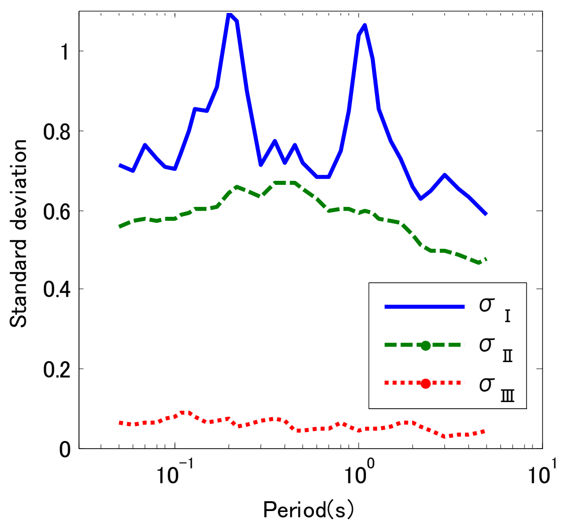

Figure 2.2. Standard Deviation of Sa of the Aftershocks

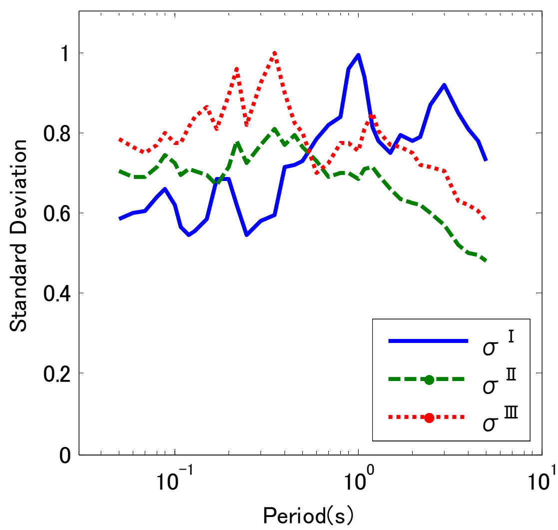

Figure 2.3. Standard deviation of Sa of the Test Earthquakes

3. EXAMINATION OF A CORRECTION FACTOR TAKING INTO ACCOUNT THE NONLINEARITY OF THE SUBSURFACE GROUND

The nonlinearity of the shallow subsurface structure is considered as one of reasons why the accuracy of the prediction for PGA, PGV and Sa at short period is not improved after the corrections. To take into account this nonlinearity, the introduction of the nonlinear regression formula as site correction term is attempted in this chapter.

Equation 3.1 is a regression formula, which is used as a new site correction term instead of Equation 2.8. $a1, a2$ and $a3$ are regression coefficients calculated for each observation point by the least square method.

$$\delta_j^{\mathrm{I}f}(I) = a1 + a2 \cdot \log(I + a3) \tag{3.1}$$

where I is PGA at engineering bedrock predicted by Equation 1.2.

The Figures 3.1, 3.2, 3.3 show the results for PGA, PGV and Sa of each period.

$\sigma^{\mathrm{II}f}$ is the standard deviation of the residuals after the site correction using Equation 3.1 instead of Equation 2.8. Standard deviations of the residuals of PGA and PGV when aftershocks have been corrected by itself are shown in Table3.1. For PGA, the correction by Equation 3.1 decreases the standard deviations than the result if no correction is performed. The increase in accuracy is not as effective as Equation 2.8. The same result is obtained for PGV.

Table3.2 shows the standard deviations of the residuals of PGA and PGV in the case test earthquakes are investigated. Standard deviation after site correction by Equation 2.8 is greater than if no correction is performed. Standard deviations of residuals after site correction with Equation 3.1 are the largest of the three both for PGA and PGV. This is because many of the residuals of the test earthquakes are plotted in the lower side of the regression formula as shown in Figure 3.1 and in Figure 3.2.

Figure 3.3 shows the nonlinear site correction terms for Sa. The trend in correction term differs from different period. Figure3.4 shows the standard deviation of the residuals of Sa when aftershocks are corrected by itself. Before performing the site correction, the standard deviation has the peak around 1.0 (s) and 0.2 (s). These peaks are no longer seen after site correction. For shorter period (T<0.2s), the standard deviation of Equation 3.1 is slightly smaller than Equation 2.8.

Figure3.5 shows the standard deviation of the residuals at all observation points when the test earthquakes are corrected. At longer period (T>0.6s), correction by Equations 3.1 increases accuracy which is comparable to correction by Equation 2.8. Contrarily, standard deviations increase at shorter period. Especially, the peak at 0.3 (s) becomes obvious, though it was not noticeable when Equation 2.8 is used as site correction term.

Site correction term as a function of PGA has been introduced to consider the effect of nonlinearity of the shallow subsurface structure. The accuracy of the correction scarcely improves compared with the constant site correction term by Equation 2.8.

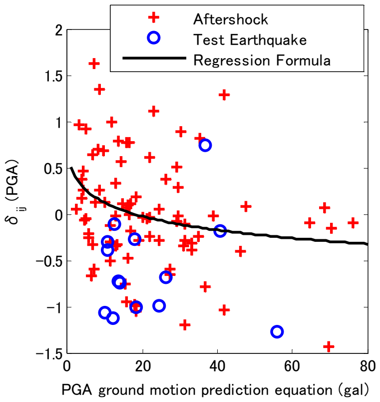

Figure 3.1. Regression formula of PGA

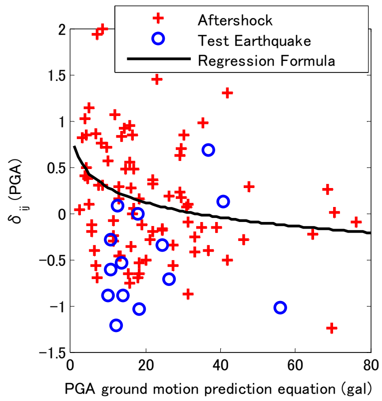

Figure 3.2. Regression formula of PGV

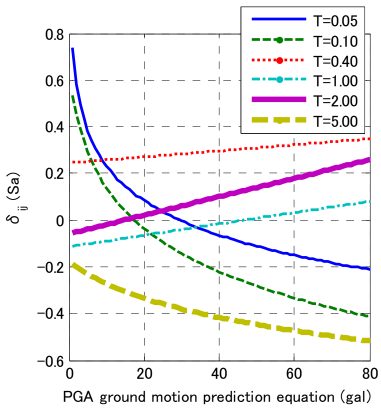

Figure 3.3. Regression formula of Sa

Table 3.1. Standard Deviation of the Aftershocks PGA and PGV Corrected for the Regression Equation

	σ^{I}	σ^{II}	σ^{IIf}
PGA	0.73	0.57	0.62
PGV	0.61	0.58	0.60

Table 3.2. Standard Deviation of PGA and PGV of the Test Earthquakes Corrected for the Regression Equation

	σ^{I}	σ^{II}	σ^{IIf}
PGA	0.58	0.72	0.84
PGV	0.63	0.71	0.77

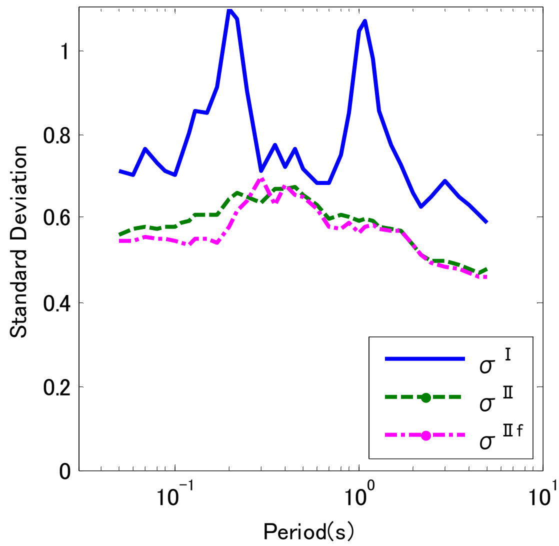

Figure 3.4. Standard Deviation of Sa of the Aftershocks Corrected for the Regression Equation

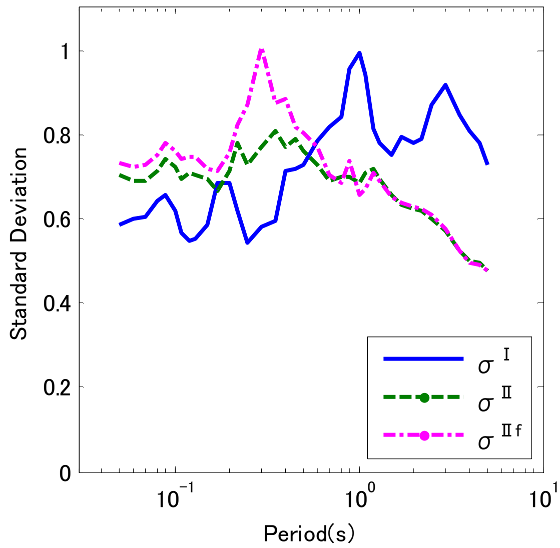

Figure 3.5. Standard deviation of Sa of the Shocks for Consideration Corrected for the Regression Equation

4. CONCLUSION

In this study, a methodology to improve a ground motion prediction equation was proposed, focusing on site characteristics and relationship between the site and epicenter locations. Aftershock records of the 2011 off the Pacific coast of Tohoku Earthquake were used for that purpose.

"Site correction term" was introduced to improve the prediction accuracy. The accuracy of Sa at longer period (T>0.6s) was much improved by introducing site correction term in a ground motion prediction equation. The prediction accuracy of PGA, PGV and Sa in shorter period, however, were not improved by introducing site correction term. The accuracy was not improved even if the nonlinear site correction term was introduced to consider the nonlinear site amplification.

“Epicenter location correction term” was also introduced to consider the effect of prediction accuracy. The correction term was not effective to improve the prediction accuracy for historical earthquakes, though it was effective if it was applied to the aftershock itself.

ACKNOWLEDGEMENT

The ground motion records and earthquake catalogue used in this study are provided by K-NET and Hi-net.

REFERENCES

Uchiyama, Y., and Midorikawa, S. (2006). Attenuation relationship for response spectra on engineering bedrock considering effects on focal depth. Journal of Structural and Construction Engineering, AIJ, 606, 81-88.

Kanno, T., Narita, A., Fujiwara, H. and Fukushima, Y. (2006). A New Attenuation Relation for Strong Ground Motion in Japan Based on Recorded Data, Bulletine of the Seismological Society of Japan 96(3), 879-897.

Si, H., Midorikawa, S. (1999). New Attenuation Relationships for Peak Ground Acceleration and Velocity Considering Effects of Fault Type and Site Condition. Journal of Structural and Construction Engineering, AIJ, 523, 63-70.

Horike, M., Nishimura, T. (2004). Attenuation relationships of peal ground velocity inferred from the kyoshin network data, Journal of Structural and Construction Engineering, AIJ, 575, 73-79.

John G. Anderson & Yasuo Uchiyama. (2011). A methodology to improve ground-motion prediction equations by including path collections. Bulletin of the Seismological Society of America, 101(4), 1822-1846.

National Research Institute for Earth Science and Disaster Prevention. (2005). A Study on Probabilistic Seismic Hazard Maps of Japan, 275

Meteorological Agency Seismological and Volcano logical Department. (2008). Technical reference materials and processing techniques summary of earthquake early warning.

Utsu, T. (2001). JISHINGAKU, KYORITSU SHUPPAN.

Tamai, M., Horike, M., Takeuchi, Y., Suzuki, H., Uetake, T. (1994). Verification of non-linearity of surficial layer using vertical-array strong-motion data. Summaries of technical papers of Annual Meeting Architectural Institute of Japan.483-484.

Uchiyama, Y., Midorikawa, S. (2003). Evaluation of Amplification factor of site classes based on strong motion records and nonlinear response analysis. Journal of Structural and Construction Engineering, AIJ, 571, 87-93.