Correction for site effects in observed ground motions and development of empirical ground-motion prediction equation for the Korean Peninsula

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1. Introduction

A ground-motion prediction equation (GMPE) is a necessary tool for seismic hazard assessment for areas of interest. In general, GMPEs are empirically developed with sufficient ground motion data. In the case of the Korean Peninsula, because of the lack of observed moderate-to-large ground-motion data, most of the GMPEs for the region were developed in alternative ways using synthetic ground-motion data calculated from stochastic simulation methods. Although Emolo et al. (2015) [1] developed an empirical GMPE for the region, data over M_L 4.0 in their dataset were included for only two earthquakes (~M_L 4.9). On the other hand, several moderate earthquakes, including the 2016 $\mathrm{M_W}$ 5.5 Gyeongju earthquake and the 2017 $\mathrm{M_W}$ 5.5 Pohang earthquake, occurred. With the help of a relatively massive dataset of those earthquakes, we have a chance to develop a more reliable version of the empirical GMPE for the Korean Peninsula.

The development of the empirical GMPE is based on the ground motions of the basement rock serving as a datum that does not change according to the conditions of overlying materials. To extract the variability of ground motions due to site effects at the surface, we estimated the site-response function based on the horizontal-to-vertical spectral ratio (HVSR) method. Then, we corrected ground motions linearly by using the function to modulate the amplitude of the surface ground motions to the bedrock level. Finally, the dataset for the development of the GMPE consisted of peak ground accelerations (PGAs) of ground motions that corrected for the surface stations and uncorrected for the borehole stations of the seismic networks administered by the Korea Meteorological Administration and Korea Institute of Geoscience and Mineral Resources.

2. Methods and Results

2.1 Estimation of the site response function

The HVSRs of the surface seismic stations were calculated using background noise data. Comprehensive procedures for the calculation of HVSR were referred to in the SESAME project and Cox et al. (2020) [2, 3]. The highest peak frequency (f_P) of the HVSR curve was selected as the resonance frequency of a site via some criteria proposed by [2]. And then, the time-averaged shear-wave velocity to 30 m depth (V_{S30}) was estimated using the f_P–V_{S30} relation [4] if V_{S30} measurement is not available. Meanwhile, the shape of the HVSR curve is known to be consistent with that of surface-to-borehole spectral ratio (SBSR) assumed as real site amplification; however, the amplitude of HVSR is known to be generally underestimated than that of SBSR. We first adjusted the amplitude of HVSR to the level of SBSR by utilizing the amplitude-correction equation based on the resonance frequency and V_{S30} [5]. As a result, site response functions (pseudo-SBSR abbreviated as pSBSR) were estimated for 75 surface stations. An example of the site response function is presented in Fig. 1.

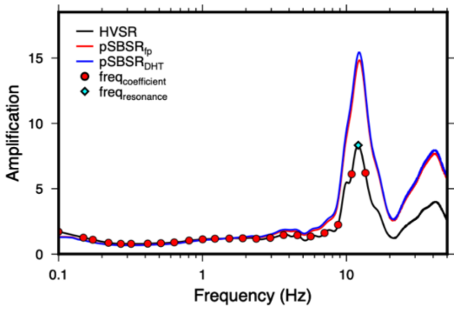

Fig. 1. An example of the site response function. A black line is the HVSR curve. Red and blue lines indicate the site response function using estimated and measured values of V_{S30}, respectively. Red circles represent frequencies applied amplitude-correction. The cyan symbol shows the resonance frequency.

2.2 Correction for site effects in ground motions

Correction for site effects in ground motions using site response function is processed in the frequency domain. Procedure of correction is as follows: 1) Calculation of an observed spectrum from a time-series data by Fast Fourier Transform (FFT), 2) design of a zero-phase linear FIR filter based on pSBSR, 3) Dividing amplitudes of the spectrum by frequency response of FIR filter (deconvolution of linear site response), and 4) transforming the corrected spectrum to time-series data by inverse FFT. As the result of linear FIR filtering, the point of the maximum amplitude in time-series is not changed but the amplitude is only adjusted. We corrected surface ground motions for 229 events, and examples of correction results are presented in Figs. 2 and 3.

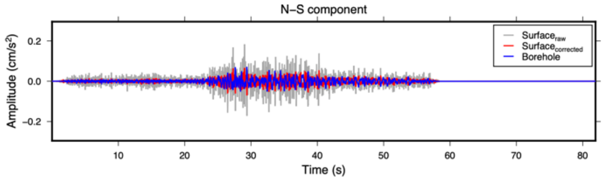

Fig. 2. Comparison of waveforms before and after correction of site effects. Gray and red lines indicate the original and corrected waveforms of the surface station, respectively. The blue line shows a waveform recorded at the borehole sensor of the same station.

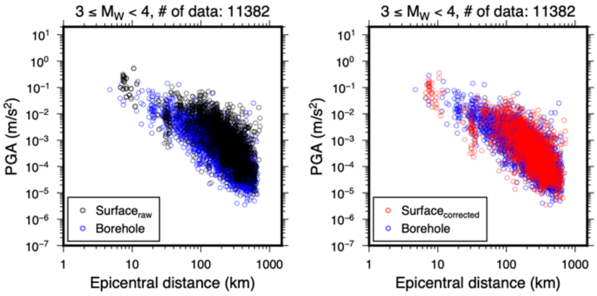

Fig. 3. Distribution of PGAs with distance. Black and red circles represent the original and corrected PGAs of the surface stations, respectively. Blue circles are PGAs of borehole stations.

2.3 Development of the empirical GMPE

We constrained the dataset within 600 km, and finally, the dataset consisted of 14910 ground-motion data. To derive the empirical GMPE using the dataset, a nonlinear mixed effects model was applied. The whole procedure was accomplished in MATLAB, and the *nlmefit* function of MATLAB was used to apply nonlinear mixed-effects regression. We used a general formulation to derive the empirical GMPE, and a reference regression model is as follows:

$$logY = a + bM + \log(\sqrt{R^2 + h^2}) + dR \qquad (1)$$

where Y, M, and R mean ground-motion parameter, moment magnitude, and epicentral distance, respectively. a, b, h, and d are regression coefficients. In regression analysis, initial values of the regression coefficients were cited from the previous study [1]; however, coefficient h, the pseudo-depth parameter, is fixed at 10 km. As the result of regression analysis, estimates of the regression coefficients were obtained. The prediction of this model for the 2016 M_W 5.5 Gyeongju earthquake is presented in Fig. 4.

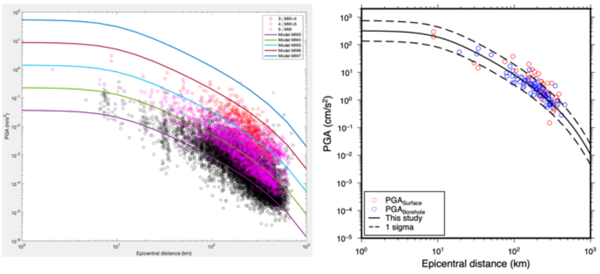

Fig. 4. (Left) Colored open circles indicate observed PGAs. Colored lines show the prediction of GMPE with M_W 3 to 7. (Right) Prediction of GMEP and observed PGAs for the 2016 M_W 5.5 Gyeongju earthquake.

3. Discussion and Conclusions

We first estimated the site response function based on the HVSR method, corrected site effects in the observed ground motions, and then derived the empirical GMPE using a dataset that is composed of ground-motion data assumed as bedrock ground motions. In the results of the correction for site effects, surface ground motions were reduced to the level of borehole ground motions in time series. Also, the distribution of corrected surface PGAs with distance is similar to that of borehole PGAs. Based on these results, the method of correction for site effects is effective in reducing surface ground motions to borehole ground motions.

In the case of residuals between observed PGA and prediction of GMPE, the pattern of underestimation is identified at 100–200 km in distribution with the epicentral distance. It is possibly caused by constructive interference of the direct waves (S_g) with the Moho reflections, i.e., S_MS waves.

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