ESTIMATION OF SOURCE, PROPAGATION, AND SITE AMPLIFICATION FACTORS USING BROADBAND SEISMIC DATA IN THE PHILIPPINES

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ABSTRACT

This study estimates the source, propagation path, and site amplification factors of the two regions in the Philippines: the Luzon and Mindanao. Using the generalized spectral inversion technique, we separated the acceleration Fourier spectra of the ground motions recorded by the Philippine Seismic Network (PSN) from 2016-2020. The source, site amplification, and anelastic attenuation (Q) factors in the two regions were estimated using the "reference event" and the "reference site" constraints. We obtained almost similar results in the Q factor using the two constraints. The "reference site" approach shows stable results in the Mindanao region. However, when using the "reference event" approach, each site's estimated site amplification factors show spectral decay in the high frequencies for the Mindanao region. The same spectral decay in the Luzon region using the "reference site" constraint. The obtained source spectra also differ among the two constraints, especially in the Mindanao region. We found that the spectral amplitudes in the higher frequencies possibly depend on the earthquake's source depth, not their source type. In the Luzon region, spectral amplitudes in the higher frequencies are observed for crustal earthquakes when we adopt the "reference site" constraint. The Q-values in the Luzon region using the reference site approach shows a weaker frequency-dependent than those estimated in the Mindanao region.

Keywords: Seismic wave attenuation, Site amplification factor, Source factor, Spectral inversion.

1. INTRODUCTION

Earthquake is one of the natural hazards that occur in a seismically active region such as the Philippines. In general, the earthquake ground motions depend on the seismic source, path, and site amplification factors. Characterization of these factors, especially the site amplification effects that may amplify the seismic motion, is important for estimating earthquake damage for future earthquakes. On the other hand, understanding the attenuation parameter such as regional Q-values is indispensable for strong ground motion prediction from the viewpoint of engineering seismology. One of the examples of site amplification effect is the 1968 Casiguran, Aurora earthquake (7.3M_w), which caused the collapse of Ruby Tower in Manila, and several major buildings near the area sustained varying levels of structural damages. The severely damaged area was about 225 km away from the epicenter. This event is comparable to the 1985 Michoacan, Mexico Earthquake (8.0 M_w), which caused severe damage in areas 400 km away from the epicenter.

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In the last half-century, different studies attempted to estimate the site amplification effects. Numerous empirical and numerical methods have been developed. The widely used method was the Standard Spectral Ratio (SSR) method (Borcherdt, 1970). Borcherdt (1970) used the spectral ratio between the sediment site and a reference site (usually on bedrock) from the same earthquake to remove the path effect. Andrews (1982, 1986) proposed the generalized spectral inversion technique and considered the geometrical spreading factor for the path term.

On the other hand, Boore (1983) added the geometrical spreading factor and anelastic attenuation of ground motion to the path term. Iwata and Irikura (1986, 1988) used reference site constraints to estimate stably the source, site, and Q factors. However, Boatwright et al. (1991) and Fletcher and Boatwright (1991) constrained the shape of the source spectrum to perform the spectral inversion. This study estimates the strong ground motions factors observed by the Philippine Seismic Network. We follow the method of Moya and Irikura (2003) in data processing, which contained the shape of the source spectrum before performing a spectral inversion. We also used an alternative approach—the reference site constraint proposed by Iwata and Irikura (1988), especially in regions where no event pairs are located to each other.

2. DATA

This study used earthquake records at 49 Satellite-Telemetered Seismic Stations (STSS) of the Philippine Seismic Network (PSN), operated by the Philippine Institute of Volcanology and Seismology (PHIVOLCS). The seismic stations were divided into three regions to facilitate more convenient spectral inversion for Luzon, Visayas, and Mindanao. Based on the PHIVOLCS SWIFT CMT catalog, we selected more than 300 earthquakes for the minimum magnitude of 4.5 and a maximum source depth of 60 km. The earthquake records are in velocity waveform in SEED data format and manually extracted from the continuous data recording based on the event catalog. The velocity waveforms were trimmed 1 minute before the P-wave onset with a 20-minute duration and converted SEED velocity waveform into SAC acceleration data format.

3. METHODOLOGY

In this study, we first automatically extract the S-wave part of the waveforms using the Husid plot (Husid, 1969) by accumulating the acceleration waveform amplitudes and find when the accumulated amplitude becomes 5% and 95% of the total energy. Generally, the 5%-95% range corresponds to the S-wave part of the waveform. Next, we remove the DC and linear trends and apply a cosine taper of approximately 5% of the 20.48-seconds duration from the head and tail of the waveform data. Then, we conduct the Fast Fourier Transform (FFT) to obtain the acceleration Fourier amplitude spectra and horizontal-to-vertical (H/V) spectral ratio of the S-wave part.

Naturally, in the frequency domain, the observed S-wave Fourier amplitude spectrum $O_{ij}(f)$ of an earthquake can be expressed as the product of these three factors— $S_i(f)$ is the source of the *i*th earthquake, $P_{ij}(f)$ is the propagation path effect, and $G_j(f)$ is the site effect at the *j*th station as expressed in equation (1):

$$O_{ij}(f) = S_i(f) \cdot P_{ij}(f) \cdot G_j(f) \tag{1}$$

This study mainly follows Moya and Irikura's (2003) method in data processing to separate these three factors and estimate each contribution to the strong ground motion, then used the Fortran program package developed by Dr. Hayashida (IISEE-BRI) for spectral inversion. For the reference event constraint, spectral shape of the source effect $S_i(f)$ is given by the ω^2 model (Brune, 1970):

$$S_i(f) = \frac{\Omega_{0i}}{1 + \left(\frac{f}{f_{0i}}\right)^2} \tag{2}$$

where Ω_{0i} is the low-frequency flat level, and f_{0i} is the corner frequency of the *i*-th earthquake. To estimate the source model in equation (2), we need to find the low-frequency flat level Ω_0 and the corner frequency f_0 of the target event. We used the obtained seismic moment in the catalog of PHIVOLCS-SWIFT CMT of the target event, and we found the Ω_0 from,

$$\Omega_0 = \frac{R \ M_o}{4\pi\rho V_s} \tag{3}$$

where R = 2/5 is the root mean square radiation pattern (Andrews, 1986), ρ = 2700 kg/m^3 is the density, and V_s = 3.2 km/s is the shear-wave velocity of the medium around the source. M_o is the seismic moment (Nm) obtained from the PHIVOLCS-SWIFT CMT catalog.

For the estimation of corner frequency f_0, we took the spectral ratios from the two events, which are relatively close to each other and have different magnitudes. The spectral ratio of the bigger magnitude event over the smaller magnitude event will remove the site and path effects and follows the ω^2 model. The f_0 can be found by comparing the average of the target events and the best-fitting function,

$$F(f) = \Omega_{os}^{ol} \cdot \left(1 + \left(\frac{f}{f_{os}}\right)^2 \Big/ 1 + \left(\frac{f}{f_{ol}}\right)^2\right) \tag{4}$$

where Ω_{os}^{ol} is the ratio of the low-frequency flat levels between the bigger and the smaller events, f_{os} is the corner frequency of the small event, and f_{ol} is the corner frequency of the big event.

In regions with no events relatively close to each other, we used the method of Iwata and Irikura (1988)— the reference site constraints. We selected a reference site with no amplification for all frequencies using the S-wave H/V spectral ratio and assumed the site amplification at this site (i.e., rock site) to be G(f)=2.0 due to the free surface effect.

4. RESULTS AND DISCUSSION

4.1 Source Effect

In the Mindanao region, we used two alternative constraints—the reference event and reference site constraints. We evaluate and compare the estimated source factors between the two constraints (see Figure 1) and found that some of the source spectra using the reference event approach do not follow the ω^2- model (Aki, 1967; Brune, 1970). However, using the reference site approach, all of the source spectra follow the ω^2- model. Moya and Irikura (2003) suggest that this is caused by the contamination of the path and site effects that distort the spectral decay from the observed spectra. We checked each spectrum and event location and found that all estimated source spectra having larger spectral amplitudes in the high frequencies are subduction zone earthquakes with depths between 20-60 km. This trend confirms the investigation of the spectral shape differences for intraslab/interplate earthquakes in northeast Japan conducted by Kasatani and Kakehi (2014). For the Luzon region, constraining the reference event was not possible due to the lack of event pairs located near each other. Instead, we only used the reference site constraint for inversion. However, the estimated source factor in the Luzon region shows similar spectral decay with those in the Mindanao region using a different approach, the reference event constraint. Both of the estimated source spectra do not follow the ω^2- model.

We failed to estimate the source, site amplification, and Q factor for the Visayas region due to little earthquakes accepted by the set criteria for inversion for the two approaches. Estimating the site and Q factor in the Visayas region will take more time until we meet the necessary event or try other criteria for selecting earthquake

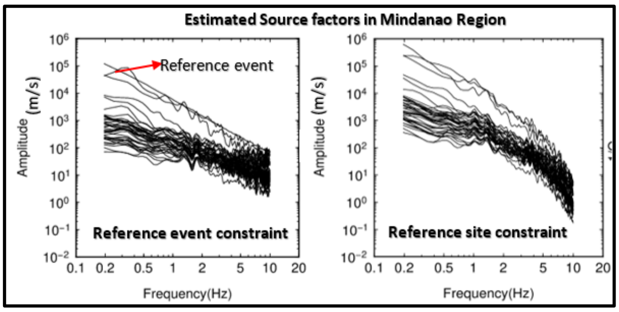

Figure 1. Estimated source factors in Mindanao Region. The left and right panel shows the source spectra of all the events used for inversion using the reference event and reference site constraints, respectively.

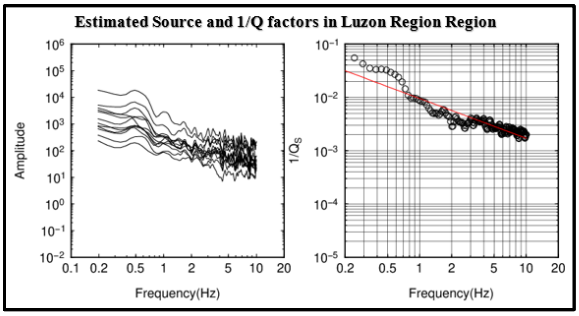

Figure 2. The estimated source factor (in the left panel) and 1/Q (in the right panel) factor results in Luzon Region using reference site

4.2 Site Effect

Figure 3 shows relations of estimated site amplification factors (thick red line) and H/V spectral ratio (thin gray line) at station LCV in the Mindanao region using two different approaches, i.e., reference event and reference site constraints. The reference site approach in the Mindanao region shows the same spectral shape between the estimated site amplification effect and the S-wave H/V spectral ratio. However, when the reference event constraint is adopted, the shape of the estimated site amplification effects are different from those of the S-wave H/V spectral ratio—showing rapid spectral decay in the higher frequencies. It only indicates that in the Mindanao region, inversion constraining a reference site has more stable results than a reference event constraint. Figure 4 shows relations of estimated site amplification factors (thick red line) and S-wave H/V spectral ratio (thin gray line) at stations RTB and TIR in the Luzon region using the reference site constraint. Here, we failed to compare the estimated site factor results between the two constraints. Instead, we compared the estimated site factor results between the Luzon and the Mindanao region. The estimated site factor at station TIR in the Luzon region using the reference site constraint (Figure 4, right panel) shows similar spectral decay as station LCV in the Mindanao region using the reference event (Figure 3, left panel). The rapid spectral decay in the higher frequencies does not depend on the constraints used for inversion but instead can be explained by f_{max} [e.g., Hanks, (1982), Boore, (1983)] and kappa [Anderson and Hough (1984)]. On the other hand, a slight deviation between the estimated site factor (thick red line) and the assumed free surface effect (G(f) = 2.0) at the reference site in Figures 3 and 4 was due to the uncertainties in the inverse problem,

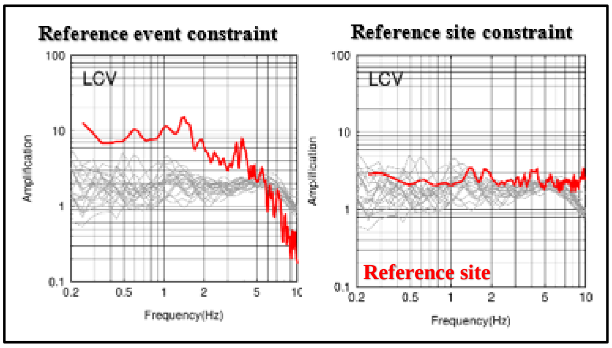

Figure 3. Comparison of estimated site factor results (thick red line) and the S-wave H/V spectral ratio (thin gray line) of LCV station in the Mindanao region using the reference site and reference event constraints.

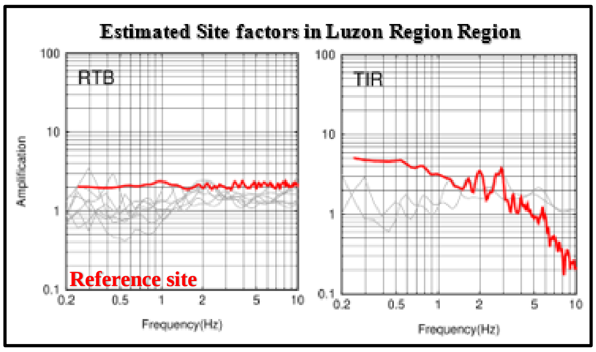

Figure 4. Estimated site factor results (thick red line) and the S-wave H/V spectral ratio (thin gray line) in the Mindanao region using the reference site constriant.

4.3 Q Effect

Figure 5 shows the comparison of the estimated Q values between the Luzon and Mindanao regions. The Q-values in the Luzon region show smaller values in comparison with those in the Mindanao region. One possible reason is that the Q-values are dependent on the traveling path or subsurface soil medium. All of the earthquakes used in the inversion in the Luzon region were crustal-type earthquakes. For crustal-type earthquakes, the seismic wave propagates in the shallow part where Q is low. On the other hand, most of the earthquakes used in the Mindanao region were subduction zone earthquakes. The attenuation model results for these two regions will be useful for various scientific studies in seismic hazard assessment and engineering seismology.

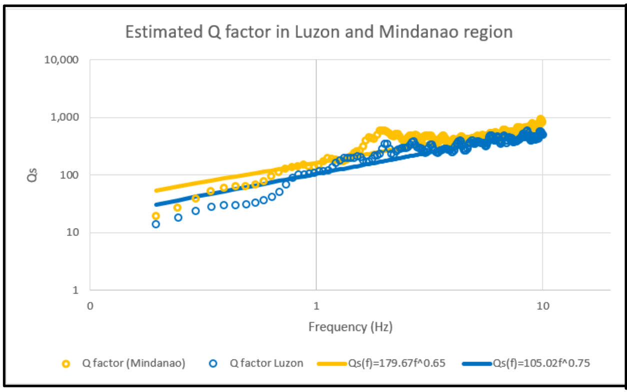

Figure 5. Comparison of estimated Q factor results between the Luzon (orange) and Mindanao (blue) region using reference site

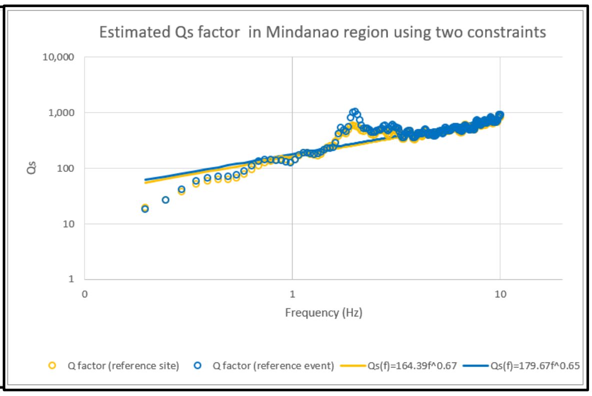

Figure 6. Comparison of estimated Q factor results in the Mindanao region using the reference event and reference site constraint.

5. CONCLUSIONS

This study applied the spectral inversion method to strong ground motion data recorded by the Philippine Seismic Network (PSN) from 2016 to 2020. Fourier spectra of the observed S-wave portion were used to estimate the source, site amplification, and Q-factor of the three regions in the Philippines— the Luzon, Visayas, and Mindanao in a frequency range from 0.1 to 10 Hz.

The Q-values obtained in the Mindanao region were almost similar for both approaches: the reference event and the reference site. We estimated the low-frequency flat level and the corner frequency of one event to model source characteristics for the reference event. We utilized the seismic moment from the catalog and the obtained corner frequency of the reference event to make the inversion process more stable. For the reference site approach, we used S-wave H/V spectral ratio information at each site and selected the station that showed a flat value entire the target frequency range. We obtained the Q-values in the Luzon region using only the reference site constraint due to the difficulty of corner frequency estimation.

In this study, the estimated site amplification factor using the reference site approach shows more stable results than the reference event. We used the reference site approach for the Luzon and Mindanao regions and estimated site factors assuming the site, which shows flat H/V spectral ratios as the reference site. It is an indication that the generalized spectral inversion technique well captures the average site amplification characteristics. However, there is a comparison between the spectral decay in the site amplification factor of the Luzon region, which follows the reference site constraint, and those with the Mindanao region that used the "reference event" constraint.

We compared the best method to follow for each region between the two approaches; the reference event and the reference site. We analyzed the source spectra obtained in both methods. We also found that the obtained source spectra in the subduction zone earthquakes using the reference event have higher high-frequency spectral levels. We also validated the relationships between higher high-frequency spectral levels and source depth ranging from 20-60 km. Estimating the site and Q factor in the Visayas region will take more time until we meet the necessary event or try other criteria for selecting earthquakes.

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