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STRONG GROUND MOTION SOURCE SCALING AND ATTENUATION MODELS FOR EARTHQUAKES LOCATED IN DIFFERENT SOURCE ZONES IN TAIWAN

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ABSTRACT

The ground-motion database collected recently in Taiwan was used for evaluation of strong ground motion models. The database contains more then 2800 acceleration records from $M > 3.0 – 3.5$ earthquakes occurred in 1993-2004. The records were obtained at rock (class B) sites located in the northern and eastern parts of Taiwan. Parameters of attenuation models (geometrical spreading and anelastic attenuation) were evaluated using acceleration spectra corrected for the site effect. The horizontal-to-vertical Fourier spectral ratio of the S-wave phase was used for the correction. The analysis was performed for three characteristic zones, namely: shallow (hypocentral depth < 30-35 km) earthquakes occurred beneath central Taiwan, shallow offshore earthquakes occurred to the east of island, and deep earthquakes (depth > 35 km). Analysis of spectra corrected for site effect, attenuation, and the influence of upper crust (*kappa*-factor) showed that the source spectra in Taiwan region may be described by the ω-square spectral model (Brune, 1970). The value of seismic moment is estimated from regional relationships between seismic moment and local magnitude. The stress parameter should be considered as a magnitude-dependent quantity (120-150 bars for M 5.0 and 250-300 bars for M 6.8) for shallow earthquakes beneath central Taiwan. The offshore and deep earthquakes are characterized by relatively constant values of the stress parameter.

Keywords: Strong Ground Motion, Attenuation Relation, TSMIP, Taiwan

INTRODUCTION

The Fourier amplitude spectrum (FAS) is widely used for strong ground motion prediction and estimating seismic hazard. One of the used approaches to describe the dependence of Fourier amplitude spectra on magnitude, distance and local soil condition, does consider the source, propagation, and site effects separately (e.g. Lam et al., 2000; Boore, 2003). First, the source spectral model (e.g. Brune, 1970) is introduced as a function of magnitude (seismic moment) and stress parameter or maximum slip velocity. Second, the source spectrum is modified as it propagates through the crust and the modification includes attenuation of ground motion with distance and amplification of motion by near surface velocity gradient. Third, the site effect is considered by means of frequency-dependent amplification functions.

The seismicity in the Taiwan area is very high, and many strong earthquakes ($M > 6$) occurred in the region during last hundred years. The ground motion database collected in Taiwan provides an

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opportunity to study both regional source scaling (e.g. Tsai, 1997) and attenuation models (e.g. Wang, 1988, 1993) for the region, as well as local site response on earthquake ground motion. The FAS models for typical site conditions were recently analyzed by Sokolov et al. (2000, 2002, 2003, 2004).

We made an attempt to re-evaluate source scaling and attenuation models for various source zones in Taiwan using a large number of acceleration records obtained during recent earthquakes (1993-2004). We used the terminology and the technique (Fig. 1a) applied by Sokolov et al. (2005a) and which is somewhat similar to that used by Chen and Atkinson (2002) for comparison of earthquake source spectra. First, the site amplification functions were evaluated for rock sites using the horizontal-to-vertical (H/V) spectral ratios (Lermo and Chavez-Garcia, 1993). Second, after removing of site effects from observed spectra by means H/V ratios, the parameters of attenuation model were evaluated. Third, the spectra were corrected for geometric spreading and anelastic attenuation (whole-path attenuation) effects, as well as for high-frequency decay (*kappa*-factor), to a reference distance of R = 1 km. These “reference” spectra were analyzed for evaluation of their dependence on earthquake source parameters (seismic moment M_0 and stress parameter $\Delta\sigma$).

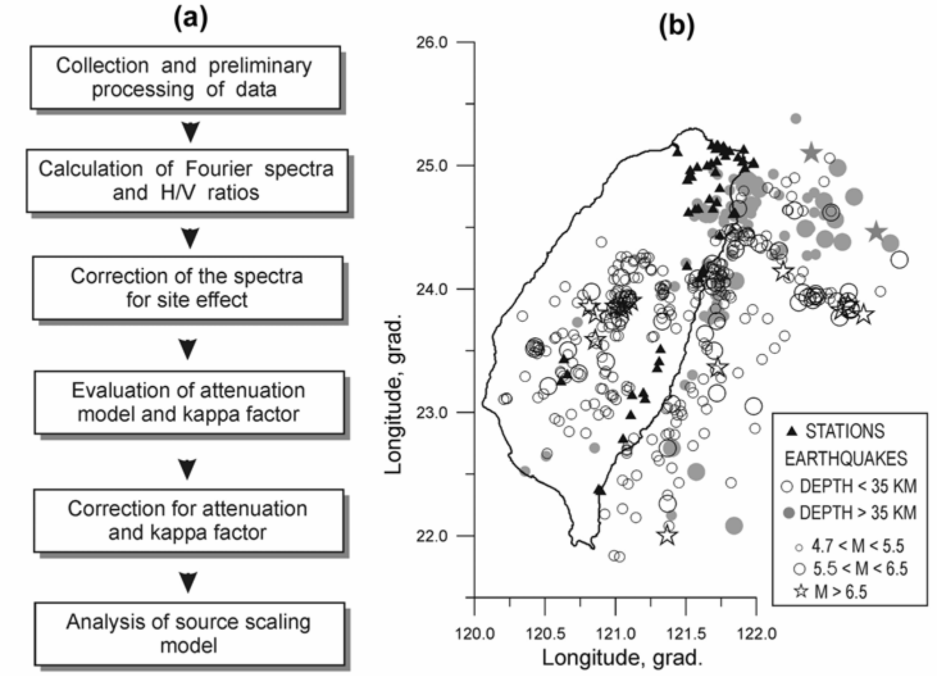

Figure 1. Evaluation of source scaling and attenuation models for Fourier amplitude spectra in Taiwan. (a) scheme of analysis; (b) distribution of rock-site stations (triangles) and earthquake epicenters (circles), records of which were used in this study.

TECHNIQUE OF ANALYSIS

The general model for the Fourier acceleration spectrum *A* at frequency *f* is given by

$$A(f) = (2\pi f)^2 CS(f)D(R, f)I(f) \qquad (1)$$

where C is the scaling factor; $S(f)$ is the source spectrum; $D(R, f)$ is the attenuation function, and $I(f)$ represents frequency-dependent and, strictly speaking, intensity- (magnitude and distance) dependent site response. A commonly used source function $S(f)$ in the Brune (1970) single-corner-frequency model is

$$S(f) = M_0 / [1 + (f / f_0)^2] \qquad (2)$$

For the model, the source acceleration spectrum at low frequencies increases as f^2 and approaches a value determined by f_0 (corner frequency) and M_0 at frequencies $f > f_0$. The value of f_0 can be found from the relation $f_0 = 4.9 \times 10^6 \beta(\Delta\sigma / M_0)^{1/3}$. Here $\Delta\sigma$ is the stress parameter in bars, M_0 is the seismic moment in dyne-cm, and β (shear-wave velocity in the source region) in km/sec.

The function $D(R, f)$ accounts for frequency-dependent attenuation that modifies the spectral shape. It depends on the source-to-site distance *R*, regional upper mantle and crustal material properties, and the frequency-dependent regional quality factor *Q* that represents anelastic attenuation. These effects are represented by

$$D(R, f) = \exp\{[-\pi f R / [Q(f)\beta]\} P(f) \tag{3}$$

where $P(f)$ is the high-cut filter. High-frequency amplitudes are reduced, through the *kappa* (κ) operator (Anderson and Hough, 1984), by multiplying the spectrum by the factor $P(f)$

$$P(f) = exp\ (-\pi\ \kappa\ f) \tag{4}$$

The *kappa*-filter is introduced to consider path-independent near-surface attenuation of seismic waves and the value of *kappa* exhibit both a region- and a site-dependent character (near surface velocity gradient).

After removing of site effect $I(f)$ from the observed spectra, Eq. 1 may be rewritten as follows

$$A_{SC}(f) = (2\pi f)^2 ([R_{\theta\phi}]FV)/(4\pi\rho\beta^3) R^{-b} S(f) \exp\{[-\pi f R/[Q(f)\beta]\} \exp(-\pi\kappa f) \tag{5}$$

where $A_{SC}(f)$ is the site-corrected spectra; $R_{\theta\phi}$ is the radiation coefficient; *F* is the free surface amplification; *V* represents the partitions of the vector into horizontal components; ρ is the density; *R* is the source-to-site distance; R^{-b} is the function that describes geometrical spreading. In general, geometric spreading of the direct waves is described using tri-linear form (e.g. Boore, 2003), namely: b=1.0 for R_1 = 50-70 km; for the transition zone where a direct wave is joined by postcritical refections from mid-crustal interfaces and the Moho-discontinuity (50-70 < R_2 < 150-170 km) b=0.0; and attenuation of multiply reflected and refracted S-waves is described by b=0.5 for R_3 > 170 km. Obviously, the critical distances should be evaluated for every region.

Correction for geometrical spreading and anelastic attenuation, and for high-frequency spectral decay (*kappa*-factor, κ) allows obtaining so-called “reference” or “apparent” spectra $A_{AP}(f)$.

$$A_{AP}(f) = (2\pi f)^2 ([R_{\theta\phi}]FV)/(4\pi\rho\beta^3) S(f) \tag{6}$$

These apparent spectra is analyzed for evaluation of their dependence on characteristics of earthquake source (seismic moment M_0 and stress parameter $\Delta\sigma$).

DESCRIPTION OF THE RESULTS

Site effect

The free-field strong-motion station sites in the Taiwan region were classified (Lee et al., 2001) based on the properties of the top 30 meters of the soil column, disregarding the characteristics of the deeper geology. Six site categories are defined on the basis of average shear wave velocity, namely: A - hard rock; B - rock; C - very dense or stiff soil; D - stiff soil; E - soft soil; F - soils requiring special studies. The existing geological and geomorphologic data were analyzed and the response spectral shape and the horizontal-to-vertical spectral ratio of response spectra data were used for the classification. However, as it has been noted recently (Lee et al., 2001; Sokolov et al., 2004; Huang et al., 2005), further studies on site classification should be carried out in the Taiwan region.

We removed the site effect from observed spectra by means of the horizontal-to-vertical (H/V) spectral ratios. The technique consists in dividing the horizontal-component shear-wave spectra at each site by the vertical component spectra observed simultaneously at that site (Lermo and Chavez-Garcia, 1993). The method assumes that the local site conditions do not significantly influence the vertical component of the ground motion. Results of application of the H/V technique, however, are affected by local and subsurface factors influencing the vertical component of ground motion. Such effects may be minimized by using data only from rock stations (e.g. Chen and Atkinson, 2002; Sokolov et al., 2005a). The H/V ratio, in addition to site amplification, also reflects some attenuation of high-frequency energy. In the frame of considered spectral model, the effect is described by the *kappa* operator (Eqs. 4 and 5).

Site Class A is not applicable in Taiwan (Lee et al., 2001), therefore we used acceleration records obtained at 53 class-B stations located in the northern and eastern Taiwan (Fig. 1b). The characteristics of the H/V spectral ratios were estimated using the whole dataset, which contains more than 2800 records from earthquakes of $M_L > 3.0$ (Sokolov et al., 2005b). In general, the H/V ratios for Class-B sites reveals typical character of rock amplification that was observed in other regions (e.g., Chen and Atkinson, 2002; Sokolov et al., 2004, 2005a), namely: average amplitude of the maximum amplification between factors of 2 and 3 and frequency of the maximum more than 3-4 Hz. In some cases, the maximum amplification is less than a factor of 2 that is close to hard rock type (Mexican rock). There are several sites that are characterized by narrow-band high-amplitude (more than a factor of 5) amplification. The peculiarity may be caused by effects of local topography (see also Lee et al., 2001), or influence of nearby building (Sokolov et al., 2005b).

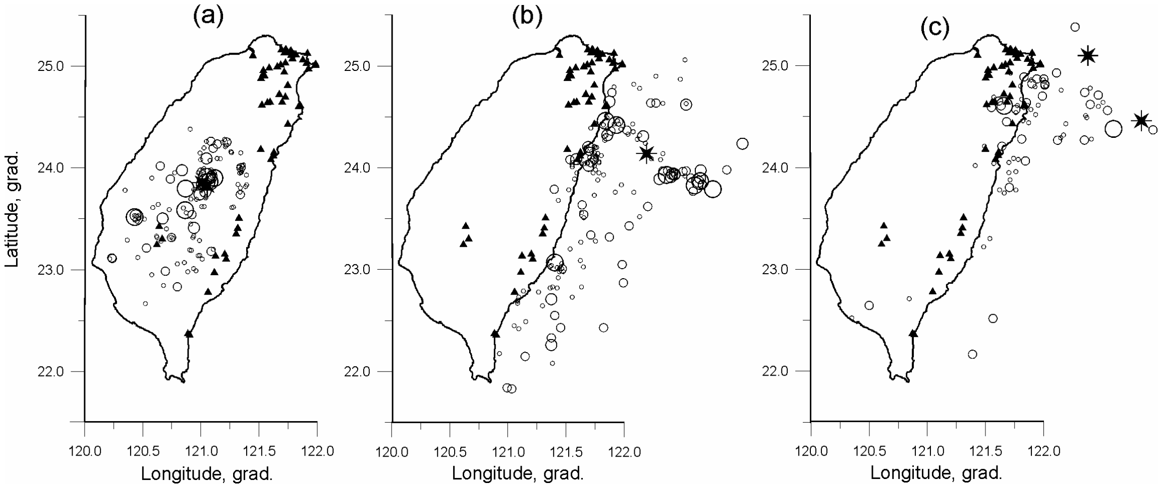

Figure 2. Distribution of earthquakes in the considered zones. (a) shallow (hypocentral depth less 30 km) earthquakes occurred beneath Taiwan (zone ST); (b) shallow earthquakes occurred outside Taiwan (zone SO); (c) deep (hypocentral depth more 30 km) earthquakes (zone DT). See Figure 1b for description of the symbols

Attenuation models

For evaluation of attenuation models for Fourier amplitude spectra we used only records from earthquakes of $M_L > 4.7$. We divided the whole dataset into three subsets following seismic zonation proposed by Loh and Jean (1997). The fist subset (zone ST) contains shallow (hypocentral depth less than 25 km) earthquakes occurred within Taiwan island (Figure 2a). The second one (zone SO) represents shallow earthquakes occurred to the east of the island under the ocean (Figure 2b). The third subset (zone DT) contains records from deep (depth > 30-35 km) earthquakes (Figure 2c).

There is unresolved trade-off between geometrical spreading and Q factors and determination of attenuation functions is not straightforward procedure (e.g. Lam et al., 2000). We have found that for shallow earthquakes the following model may be used for description of geometrical spreading (R^{-b}), namely: b=1.0 for R_1 = 50 km; and b=0.0 for R_2 > 50 km. For evaluation of the Q-model we used the procedure applied in our previous studies (Sokolov et al., 2000; 2002). The procedure is based on assumption that for a subset of data having approximately the same magnitude (M ± 0.25) the proper attenuation model should provide minimum variance of the spectral amplitudes $\log A_{SC}(f)$ for all considered frequencies at reference distance R=1 km. Table 1 summarizes parameters of anelastic attenuation $Q(f)$ for the considered earthquake zones. For deep earthquakes, the Q-model was evaluated using several characteristic distances R_1. The value of Q_0 increases with increasing of characteristic distance and the best results (i.e. minimum variances) were obtained for R_1 = 50 km.

Table 1. Parameters of the optimal Q-models for considered earthquake zones in Taiwan

Magnitude range	Distance range, km	Number of records used for analysis	$Q(f)=Q_o f^n$	
			Q_0	n
Zone ST				
4.8 – 6.7 (5.2 – 5.7)*	10 – 180 (12-78)*	257 (18)*	80 (35)*	0.9 (1.0)*
Zone SO				
4.8 – 6.7	7 - 180	447	120	0.8
Zone DT				
4.8 – 6.7	40– 250	710	60 (140)**	1.0 (1.2)**

* data for stations located in the central part of the island (CHY array, see Figure 1b)
** the values are given for R_1 = 50 km and 100 km (in parentheses)

The review of the recent studies of attenuation of earthquake ground motion for Taiwan region was prepared by Wang (1993). The trade-offs between geometric and anelastic attenuations, as well as the use of different types of seismic waves in these studies, make difficult, or even impossible, direct comparison the existing relations with our results. For the case of shallow earthquakes (hypocentral depth less than 25 - 30 km) our results and the existing ones reveal the similar character. The attenuation of S waves is stronger in central Taiwan than in northern part of island and offshore. The direct comparison may be made with relatively old study by Chang and Yeh (1983), which determined the quality factor Q_A from accelerograms. For northeast Taiwan, their relation is the following: $Q(f)=98f^{1.0}$. Our study resulted in $Q(f)=80f^{0.9}$ for central Taiwan and $Q(f)=120f^{0.9}$ for offshore earthquakes.

However, for the case of deep earthquakes, we obtained the relatively low quality factor Q_0 that, at first, seems strange and does not agree with other studies. For example, Chang and Yeh (1983), for quality factor Q_A determined from accelerograms, reported $Q(f)=225f^{1.1}$ for deep (depth less 80 km) earthquakes. However, the authors used a limited set of acceleration records regardless the site condition, namely: only 71 accelerograms from both shallow and deep earthquakes. In our study we used more than 700 records from deep earthquakes and our results consider the geometric and anelastic attenuations jointly. The value of Q_0 increases with increasing of characteristic distance R_1.

Source scaling

For analysis of source scaling model, after removing the site effect, the observed spectra were corrected for geometric spreading and anelastic attenuation (whole-path attenuation) effects to a reference distance of R = 1 km. The reference R1-spectra still contain effect of *kappa*-factor or high-frequency spectral decay (Eqs. 4-5). The parameter *kappa* may differ considerably from site to site even for Class-B category (e.g. Sokolov et al., 2005a). In this work, we used the following procedure for evaluation of the parameter. As it follows from Eqs 1 and 2, the amplitude level of acceleration spectra should be flat at frequencies $f > f_0$. Thus, the proper value of *kappa* yields approximately the same amplitudes of acceleration spectra at intermediate and high frequencies. For example, for the ST zone and two subsets of data, namely: M_L 4.8 – 5.2 and M_L 6.2 – 6.7, the proper values of *kappa* are about 0.035 and 0.05 for the first and second subsets correspondingly. Note that the values reflect generalized *kappa* effect averaged for several Class-B sites.

The evaluated values of *kappa* slightly increase with the increase of magnitude. Atkinson and Silva (1997) showed that the parameter *kappa* should be considered as a magnitude-dependent quantity, as the result of nonlinear behavior of the surface rock. On other hand, the phenomenon may be caused by peculiarities of the empirical ground-motion database. To ensure the sufficient signal-to-noise ratio in the high-frequency domain for small earthquakes, the records should be obtained at sites that are characterized by relatively small values of *kappa*. Also, as far as the *kappa* factor may reflect effect of the earthquake source, the influence of the source could not be neglected.

Let us assume, as first approximation, that source radiation from the Taiwan earthquakes may be described by a single-corner-frequency ω-square spectral model (Eqs. 1-2). Thus, after correction for the *kappa*-effect, for the corrected spectra there are two source parameters, which determine shape and amplitude level of the spectra, namely: the seismic moment M_0 and the stress parameter $\Delta\sigma$. The magnitude of earthquakes in the database, which used in this study, is expressed in term of local magnitude (M_L). The relations between local magnitude and seismic moment for earthquakes in Taiwan region were discussed by Wang (1992). The relations are the following.

$$\log M_0(WLC) = (14.571 \pm 1.683) + (1.598 \pm 0.236) M_L \tag{7}$$

by Wang et al (1989) and

$$\log M_0(LC) = (19.043 \pm 0.533) + (0.914 \pm 0.035) M_L \tag{8}$$

by Li and Chiu (1989). For magnitudes less than 6.65, the values of $M_0(WLC)$ are larger than those of $M_0(LC)$ and vice versa. We checked the both relations.

The values of the stress parameter in the model were evaluated by finding a value of $\Delta\sigma$, which minimizes a measure of misfit between the apparent and modeled spectra. The analysis was performed as follows. The modeled spectra were calculated for seismic moments corresponding to the central magnitude of every M_L-subset and several values of stress parameter. Necessary parameters in Eqs. 1-3 were accepted as follows: $R_{\theta\phi}$ = 0.55, F = 2.0, $V = 1/\sqrt{2}$, ρ = 2.8 g/cm^3, β = 3.6 km/sec and 4.2 km/sec for shallow and deep earthquakes, correspondingly.

Analysis of apparent spectra, i.e. spectra corrected for site effect, geometric and anelastics attenuation, as well for the influence of upper crust (*kappa*-factor), shows that the source spectra in Taiwan region may be described by single-corner-frequency ω-square spectral model (Brune, 1970). The relation between seismic moment (M_0) and local magnitude M_L proposed by Wang et al (1989) may be used for earthquakes of $M_L < 6.5$. For magnitudes more than 6.5, however, the relation fails to describe the low-frequency part of the apparent spectra. The relation proposed by Lee and Chiu (1989), which resulted in smaller seismic moment value for this magnitude range, provides much better agreement between apparent spectra and model.

The stress parameter $\Delta\sigma$, which controls high-frequency spectral amplitudes in the model, should be considered as a magnitude-dependent quantity for shallow earthquakes beneath Taiwan (the ST zone).

The stress parameter increases from 120-150 bars for M_L 5.0 up to 250-300 bars for M_L 6.8. This fact agrees with results obtained by Tsai (1997) after analysis of a few tens earthquakes in Taiwan region. The offshore (the SO zone) and deep (the DT zone) events do not reveal the dependence of stress parameter on magnitude. For the offshore earthquakes the stress parameter is about 100 bars; however the deep earthquakes are characterized by relatively high values of stress parameter (250-300 bars).

DISCUSSION

The obtained source scaling and attenuation models represent the spectra that are free from the effects of near-surface crustal attenuation (*kappa*-factor) and site amplification. After introducing a proper value of *kappa*, the modeled spectra can be considered as so-called “Very Hard Rock” or VHR spectra (Eq. 5). The VHR spectra provide a basis for evaluation of attenuation relations for such ground motion parameters as peak ground amplitudes (PGA) or response spectra (PSA) using stochastic simulation and correspondent amplification function (parameter $I(f)$ in Eq. 1). We tested our spectral models by calculation of theoretical relationships between ground motion parameter, magnitude and distance and comparison with the data observed at Class-B sites. The stochastic simulation technique (Boore, 1983, 2003) was used to generate time histories of ground motion.

One of the most important parameters used for stochastic predictions is the duration model because it is assumed that most (90 per cent) of the spectral energy given by Eq. 1 is spread over a duration τ=0.9 of the accelerogram. Wen and Yeh (1991) studied strong motion duration for the Taiwan region. They obtained the following relationship for ground acceleration

$$\tau_{0.9} = 0.430\exp(0.504M_L) \pm 2.749 \tag{9}$$

for the whole data set including alluvium site and rock site records. Unfortunately, they did not present the relationships between the duration and distance; although they did mention that the duration has a slight tendency to increase with distance up to about 80 km. Sokolov et al. (2000) had also tested another distant-dependent relationship (Shteinberg, 1986), namely:

$$\log_{10}\tau_{0.9} = 0.207M + 0.264\log_{10}R - 0.65 \pm 0.19 \tag{10}$$

Comparison between observed PGA values (both horizontal components) and predicted PGA for magnitude range M_L 5.2-5.7 (ST zone) is shown in Fig. 3. Simulated PGA values were obtained using two duration models (Eqs. 9 and 10) and were averaged from 40 simulations. Two general spectral models were used for the modeling, namely: the VHR spectra (Eq. 5), which is free from site effects, and the Class-B spectra, which was calculated as the VHR spectra multiplied by generalized Class-B amplification function. Peak amplitudes of ground acceleration may be sensitive to amplitude of particular peaks in frequency-dependent site amplification function. The procedure of averaging empirical amplification functions leads to smoothing of the peaks. Therefore, the use of mean-amplitude amplification in prediction of site-dependent PGA values may result in underestimation of the parameter. During the comparison, we used three variants of the amplification model, namely: mean (Class-B model), mean + 1 standard deviation (Class-B1 model), and mean + 2 standard deviation (Class-B2 model) amplitudes of site amplification. The values of seismic moment and stress parameter for the modeling were accepted as 1.5 x 10^{23} dyne cm and 150 bars that corresponds to earthquake of M_L=5.5.

The VHR prediction (curve 1) may be considered as an estimation of the lowest PGA level. When applying the average class-B amplification, the use of mean + 1 standard deviation amplitudes of amplification (curve 2) provides a better agreement with the observed data. The mean + 2 standard deviation amplitudes of amplification provide a reasonable upper limit of the PGA level. The difference between two considered models of duration seems not to be significant. The average value of residuals (model bias) between the observed PGA and PGA modeled using mean + 1 standard deviation amplitudes of amplification for the distance-independent model (Eq. 9) is -0.159 and -0.12

for distance-dependent model (Eq. 10); standard deviation of residuals is 0.29 and 0.3, correspondingly. The average value of residuals is close to zero when using mean + 0.92-0.95 standard deviation amplitudes of amplification.

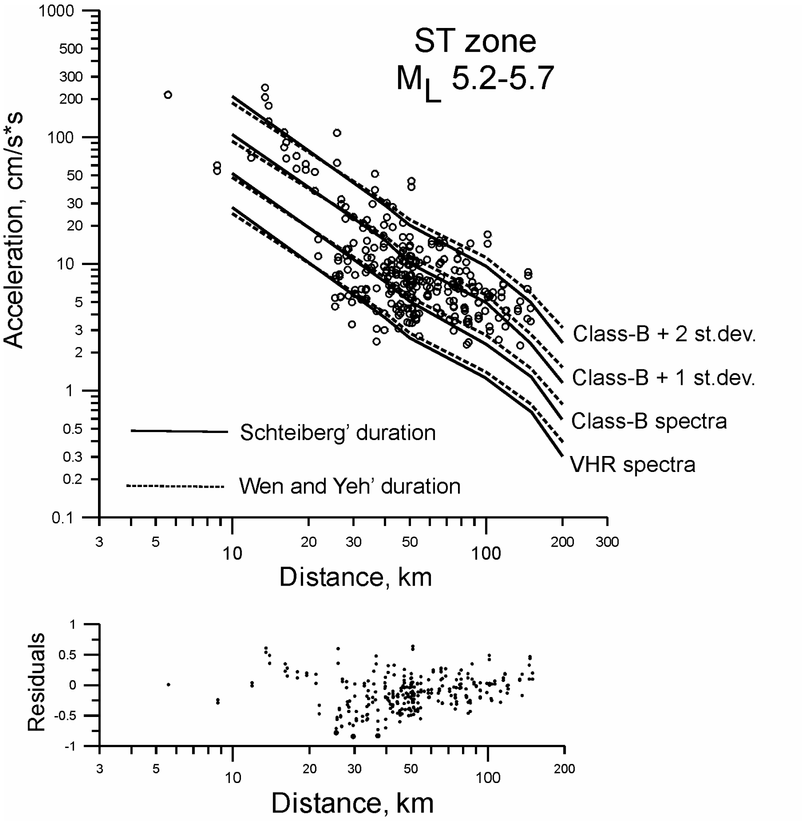

Figure 3. Application of the developed spectral models for evaluation of peak acceleration; ST zone. Comparison between observed PGA values (horizontal components, open circles) and peak ground accelerations (lines) predicted using the correspondent spectral model and two duration models (lines, see text for description of the models). The residuals are defined as the ratio between the observed data and PGA values predicted using Class-B+1 st.dev. spectra.

The comparison between empirical and modeled 5% damped response spectra for earthquakes in the DT zone is shown in Fig. 4. Two magnitude ranges (M_L=5.2-5.7, M_0=1.5 x 10 ^{23}, $\Delta\sigma$=250 bars; M_L=6.2-6.7, M_0=6.5 x 10 ^{24}, $\Delta\sigma$=300 bars) and two characteristic distances R_C were selected. The response spectra calculated from earthquake recordings that were obtained within the small intervals around the characteristic distances (R_C ± 5-10 km) were averaged to produce characteristic observed spectra. The modeled response spectra were calculated for the characteristic distances using three models of input Fourier spectra, namely: the VHR model, the Class-B model, and the Class-B1 model. The distance-independent duration model of Wen and Yeh (1991) was used. As can be seen, the response spectra, which were modeled using generalized Class-B1 model, show very good agreement with the averaged empirical spectra in the broad frequency range (0.3–10 Hz).

CONCLUSIONS

The results of the study may be considered a basis for analysis of site effects using non-reference-site approach, such as “empirical-inferred” amplification technique (Atkinson and Cassidy, 2000), or “very hard rock” method (Sokolov et al., 2000, 2003), which are based on spectral model for a bedrock interface. Such analysis will provide necessary input data for region- and site-dependent seismic hazard analysis in Taiwan. The developed spectral models together with frequency-dependent site amplification functions may be also used for development of attenuation relations for peak amplitudes and response spectra. As a future task, complicated $Q(f)$ function should be analyzed together with frequency-dependent critical distance in geometric scatter. It may be also useful to apply a layered Q-model for analysis of ground motion attenuation for deep earthquakes.

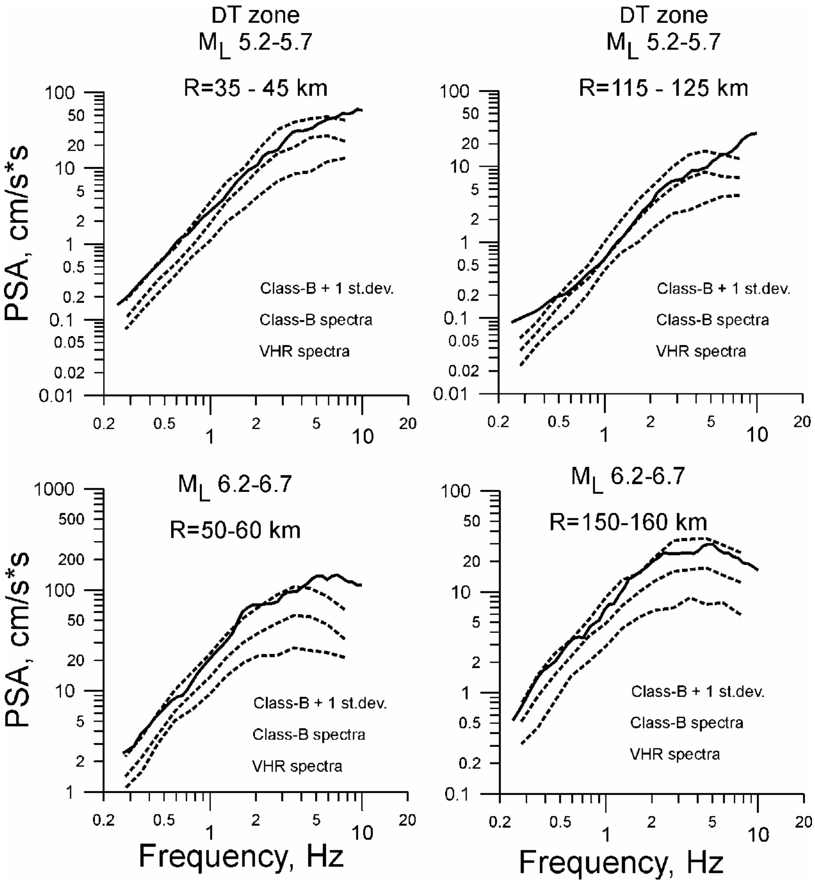

Figure 4. Application of the developed spectral models for evaluation of response spectra; DT zone. Comparison between observed response spectra averaged for selected ranges of distances R and magnitude M_L (solid lines) and response spectra modeled the developed spectral model and averaged Class-B site amplification (dashed lines).

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