Empirical Models for Site- and Region-Dependent Ground-Motion Parameters in the Taipei Area: A Unified Approach

Vladimir Yu. Sokolov, Chin-Hsiung Loh, M.EERI, and Kuo-Liang Wen

We calculated peak ground accelerations and response spectra for the Taipei area using stochastic simulation technique on the basis of recently obtained empirical models. The source, path and site effects were characterized separately on the basis of the analysis of a large collection of ground-motion recordings obtained since 1991 in the Taiwan area. The simple ω-squared Brune's point-source model combined with regional anelastic attenuation (Q) and duration ($\tau_{0.9}$) models provide a satisfactory estimation of ground-motion parameters for rock sites. Effects of local site response are considered by means of empirical soil/bedrock spectral ratios calculated as ratios between spectra of actual earthquake records and those modeled for hypothetical "hard rock" site. The results of the simulation demonstrate that this combination of source, path and site response models provides an accurate prediction of "site- and region-dependent" ground-motion parameters for the Taipei basin for the broad range of earthquake magnitudes, distances and site conditions. The model, with a set of generic soil profiles, can be considered as an efficient tool for estimating of design input ground motion parameters in the Taipei basin both in deterministic (scenario earthquakes) and probabilistic ("site- and region-dependent" Uniform Hazard response spectra) seismic hazard assessment.

INTRODUCTION

Procedures of seismic hazard assessment are based on ground motion attenuation relationships that can be derived from statistical analyses of recorded ground motions or, in conditions of limited strong-motion records, from the available literature sources. Ideally, these attenuation models should consider regional earthquake source and propagation path effects and local site response peculiarities. The characteristics of site response, in turn, depend on input motion characteristics (amplitude, frequency content, etc.) and, therefore, on the source and propagation path features (e.g., Aki 1988; Aki and Irikura 1991; Bard 1995). Available empirical ground motion models (see Abrahamson and Shedlock 1997, for recent review), even if developed for different tectonic categories of earthquakes, have a large degree of uncertainty. Special studies should be carried out in order to determine whether these global models can be used in any specific case (Somerville 1998).

The needs of realistic representation of source, path and site effects require a model that considers these three factors separately. The approaches to constructing the model include

(VYS) Geophysical Institute, Karlsruhe University, Hertzstr. 16, 76187 Karlsruhe, Germany
(CHL) National Center for Research on Earthquake Engineering, 200, Sec. 3, Hsinhai Rd., Taipei, Taiwan
(KLW) Institute of Applied Geology, National Central University, Chung-li, Taoyuan County, Taiwan

statistical analysis of available records in order to obtain an empirical relationships with a large number of regression coefficients, as well as combination of different theoretical models of source rupture process, propagation path and local site response with analysis of empirical data. Recently developed computational procedures and increase of speed and memory of modern computers should allow to model the effects of laterally varying geological structures during an earthquake characterized by a complex rupture process (e.g., Irikura et al. 1996; Pitarka et al. 1998). This approach seems to be effective for prediction of strong-motion parameter for a single (or a few) scenario earthquake, but it is unapplicable for probabilistic seismic hazard assessment which is based on consideration of multiple earthquakes occurring at different distances.

One of the most widely used approaches to prediction of strong ground-motion parameters is stochastic modeling (Hanks and McGuire 1981; Boore 1983; Boore and Atkinson 1987, and others), which initially was based on the Brune's (1970) ω^{-2} point-source spectrum model and revealed a good ability to describe peak values and spectral amplitudes of ground motion in western U.S. (Boore 1986). The applicability of the ω^{-2} model for strong ground motion for earthquakes in different seismic regions has been studied for Japan (Irikura 1986; Takemura and Ikeura 1988; Kamiyama 1989), Italy (Rovelli et al. 1988), Caucasian region (Sokolov 1997, 1998a), Taiwan (Hwang and Kanamori 1989; Tsai 1997; Sokolov et al. 2000a) and other areas. More complex so-called two-corner frequency models have been proposed (e.g., Boatwright and Choy 1992; Atkinson 1993; Atkinson and Silva 1997) to overcome the limitations of the simple spectral model, to describe regional features of seismic waves excitation and propagation and to account for finite-fault effects. The stochastic ω^{-2} model is applied also for strong ground motion simulation near a large earthquake source by summation of radiation from small subsources (Chin and Aki 1991; Schneider et al. 1993; Frankel 1995; Irikura et al. 1996; Beresnev and Atkinson 1997, 1998; Beresnev et al. 1998). Empirical attenuation models are used to describe the propagation path effects, and site response is described by empirical amplification characteristics (e.g., Schneider et al. 1991; Beresnev et al. 1998), or by a geological model in combination with numerical simulation (Irikura et al. 1996).

One of the major advantages of the stochastic model is its ability to utilize available empirical ground motion records and to be adapted easily to regional peculiarities of strong ground motions. The accuracy and reliability of the updated model depends entirely on the quality and amount of empirical data used. Therefore, the large amount of ground motion acceleration recordings, obtained during the realization of the Taiwan Strong Motion Instrumentation Program (TSMIP) since 1991 (Kuo et al. 1995) provides a unique opportunity to study source scaling and attenuation relations for a wide range of earthquake magnitudes and distances. In this study we use the stochastic simulation technique to calculate strong-motion parameters (peak ground accelerations and response spectra) for the Taipei basin considering source, path and site effects. Parameters of the source scaling and attenuation models, as well as the characteristics of the site response, were derived from the analysis of available strong ground motions recordings. The focus of this study is to check whether the combination of recently established source-path-site response models allows us to calculate realistic "site- and region-dependent" strong-motion estimations for the Taipei area and, therefore, to be used a basis for the probabilistic seismic hazard assessment.

COMPUTATIONAL MODEL

SOURCE SCALING AND ATTENUATION MODELS

A collection of ground-motion recordings (1380 acceleration records) of small to moderate ($4.5 \leq M_L \leq 6.5$) earthquakes obtained at distances up to 200 km was used in our previous study (Sokolov et al. 1999, 2000a) to study source scaling model and attenuation relations for the Taiwan region. The general model of radiated spectra, describing the Fourier acceleration spectrum A at frequency f, was considered in the following way (Boore 1983)

$$A(f) = (2\pi f)^2\, C\, S(f)\, D(R,f)\, I(f), \tag{1}$$

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 site response. The scaling factor is given by

$$C = (\langle R_{\theta\phi}\rangle F V) / (4\pi \rho^3 R^b), \quad (2$$

where $\langle R_{\theta\phi}\rangle$ is the radiation coefficient, F is the free surface amplification, V represents the partitions of the vector into horizontal components, ρ and b are the density and shear velocity in the source region, and R is the hypocentral distance.

A commonly used source function $S(f)$ in the Brune's model (1970) is

$$S(f) = M_0 / [1+(f/f_0)^2] \tag{3}$$

For the Brune's 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 in km/sec. The level of the spectrum remains constant for frequencies above f_0 until the cut-off frequency f_{max} is approached. The amplitude of the spectrum decays rapidly at frequencies above f_0.

The function $D(R, f)$ accounts for frequency-dependent attenuation that modifies the spectral shape. It depends on the hypocentral distance (R), regional crustal material properties, the frequency-dependent regional quality factor Q, and f_{max}. These effects are represented by the equation

$$D(R,f) = exp\,[-\pi f R / Q(f)\, \beta\,]\, P(f, f_{max}), \tag{4}$$

where $P(f, f_{max})$ is a high-cut filter. We used the P-filter proposed by Anderson and Hough (1984)

$$P(f) = exp\,(-\pi \kappa f) \tag{5}$$

The results of our previous study reveal that the acceleration spectra of the most significant part of the records, starting from the S-wave arrival, for hypothetical *very hard rock* (VHR) sites (ρ = 2.8 gm/cm^3, β = 3.8 km/sec, $I(f) = 1$) in the Taiwan, area can be modeled accurately by the single-corner frequency Brune's ω^{-2} source model, with the magnitude-dependent stress parameter $\Delta\sigma$, determined using recently proposed regional relationships between seismic moment (M_0) and magnitude (M_L) (Li and Chiu 1989)

$$\log_{10} M_0 = 19.043 + 0.914\, M_L, \tag{6}$$

and between $\Delta\sigma$ and M_0 (Tsai 1997)

$$\log_{10} \Delta\sigma = -3.3976 + 0.2292 \log_{10} M_0 \pm 0.6177 \quad (7)$$

Tsai also noted that the $\Delta\sigma$ values estimated using his relationships should be treated as upper-boundary values.

Frequency dependent attenuation of spectral amplitudes with distance may be described using a quality factor $Q = 225 f^{1.1}$ for deep (depth more than 35 km) earthquakes and $Q = 125 f^{0.8}$ for shallow earthquakes, and a kappa filter (κ = 0.03-0.04) may be used to modify the spectral shape. When considering geometrical spreading in the form $1/R^b$ (Equation 2), attenuation of the direct waves is described using $b = 1.0$ for $R_1 < 50$ km; for transition zone where the direct wave is joined by postcritical reflections from mid-crustal interfaces and the Moho-discontinuity ($50 < R_2 <$ 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. The obtained source scaling and attenuation models allow for a satisfactory prediction of the peak ground acceleration for rock sites and, combining with generalized soil amplification curves, for soil sites, for magnitudes $4.5 \le M_L \le 6.5$ and distances up to about 200 km.

Actually, two spectral models were developed for the Taiwan region (Sokolov et al. 2000a), namely, model 1—the above mentioned ω-square model for "very hard rock" (VHR) sites (see Figure 1a), and model 2—empirical spectra ("average soil") estimated for a reference distance R = 1 km (Figure 1b, solid lines). These empirical "average soil" spectra were estimated for magnitude ranges $5.0 < M_L < 5.5$; $5.5 < M_L < 6.0$, and $6.0 < M_L < 6.5$. A collection of recordings from the recent M_L = 7.3 Chi-Chi earthquake of 21 September 1999 (Loh et al. 2000) allows to test the applicability of these models in the case of a large earthquake. For the purposes of preliminary and simple verification, we compared the peak ground acceleration (PGA) values observed during the Chi-Chi earthquake with the PGA's calculated using the regional spectral models. In order to extend the model 2 to larger magnitudes, the logarithmic increments (β_M) of spectral amplitudes (A) per unit of magnitude were calculated for considered frequencies in the following form: $\beta_M(f) = \Delta\log A(f) / \Delta M$. Figure 1c shows the values β_M which were calculated for the above mentioned magnitude ranges, and the averaged values which were used for estimation of spectral amplitudes for the larger magnitudes (Figure 1b, dashed lines). The relation $\beta_M(f)$ shows that the values of β_M increase with decreasing of the frequency and they are nearly constant in the low-frequency range. In other words, as the source energy increases, the intensity of low-frequency vibrations increases more rapidly than that of high-frequency vibrations. This fact agrees with the results of previous studies of the β_M coefficients (e.g., Chernov 1989; Sokolov 1998c). When using model 2, the "average soil" spectrum at a distance R was calculated by multiplication of the "reference distance" spectrum by $R^b exp(-\pi f R/Q(f)V_S)$. The calculation of the spectra on the basis of model 1 was performed using the regional relationship between seismic moment (M_0) and local magnitude (M_L) (Li and Chiu 1989) and between stress parameter $\Delta\sigma$ and M_0 (Tsai 1997) (Equations 6 and 7). The accepted values of these parameters are as follows: $M_0 = 5.2 * 10^{25}$ dyne cm, $\Delta\sigma$ = 400 bars. It is necessary to note, that we deliberately do not consider the values that were reported for the earthquake. Our goal was to estimate, whether is it possible to use our spectral model which is based on averaged regional relationships. However, the parameters of large asperity (subsource) determined by Irikura et al. (2000) for the Chi-Chi earthquake main shock are approximately the same: $M_0 = 11 * 10^{25}$ dyne cm, $\Delta\sigma$ = 200 bars. The PGA values were calculated using stochastic simulation technique (Boore 1983) and the regional relationship between ground motion duration ($\tau_{0.9}$) and magnitude (Wen and Yeh 1991) $\tau_{0.9} = 0.43 exp(0.504 M_L)$.

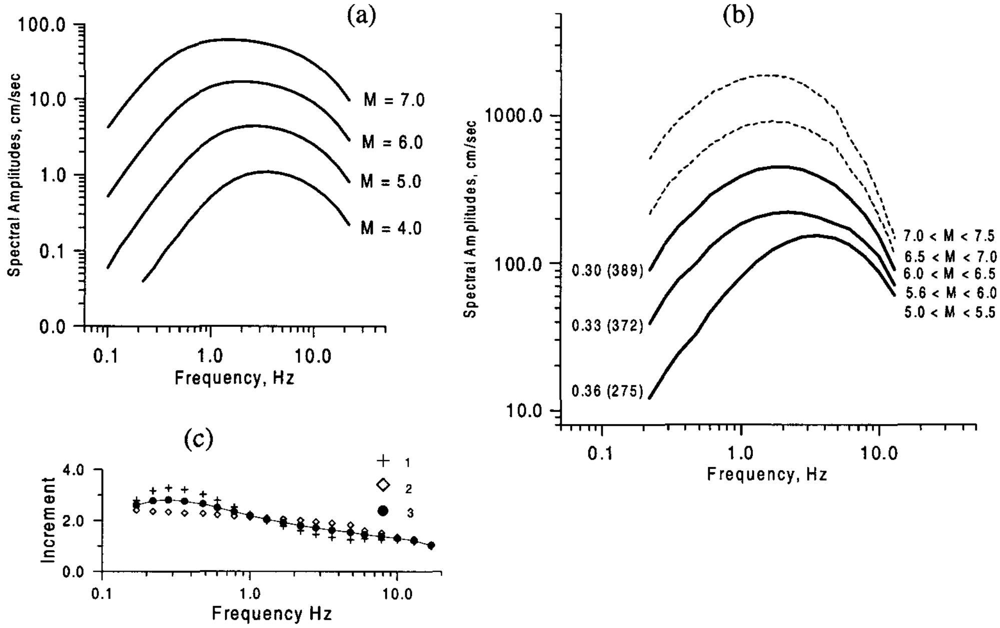

Figure 1. Spectral models for the Taiwan region. (a) *very hard rock* (VHR) spectra at distance 10 km. (b) Solid lines show empirical "average soil" spectra, reference distance 1 km. Numbers near the curves denote standard deviation and number of the used records (in parenthesis). Dashed lines show the spectra estimated using the coefficients β_M. (c) Frequency dependence of the coefficients β_M (see text) calculated using different magnitude ranges (1 – 5.5 < M < 6.0 versus 5.0 < M < 5.5; 2 - 6.0 < M < 6.5 versus 5.5 < M < 6.0; 3 – averaged values).

Figure 2 shows the comparison between empirical PGA (horizontal components) and those calculated using model 1 (VHR spectra), and model 2 (empirical "average soil" spectra). A set of 40 synthetic acceleration time functions was generated, and the resulting PGA is estimated as an average value. The distribution of the PGA values is shown versus the shortest distance to the rupture (fault plane). When calculating theoretical PGA's, the minimum site-rupture distance to be used in Equations 2 and 4 was accepted as R =10 km, because, as it has been revealed from empirical attenuation models, the ground motion parameters vary insignificantly with distance near the earthquake source (the so-called near-field zone). The dimension of this zone (the shortest distance to the source plane) for an M = 7 earthquake is approximately equal to 10 km (Chernov 1989). It is seen that the peak amplitudes calculated using the VHR model are less than the observed amplitudes and provide a kind of "lower limit" estimation. The "average soil" model combined with effective duration 20 sec, in general, provides a satisfactory prediction for the case of the Chi-Chi earthquake. The average value of the residuals (model bias) is about -0.027 for this case (i.e., practically equal to zero). The standard deviation of the residuals is about 0.22 log unit

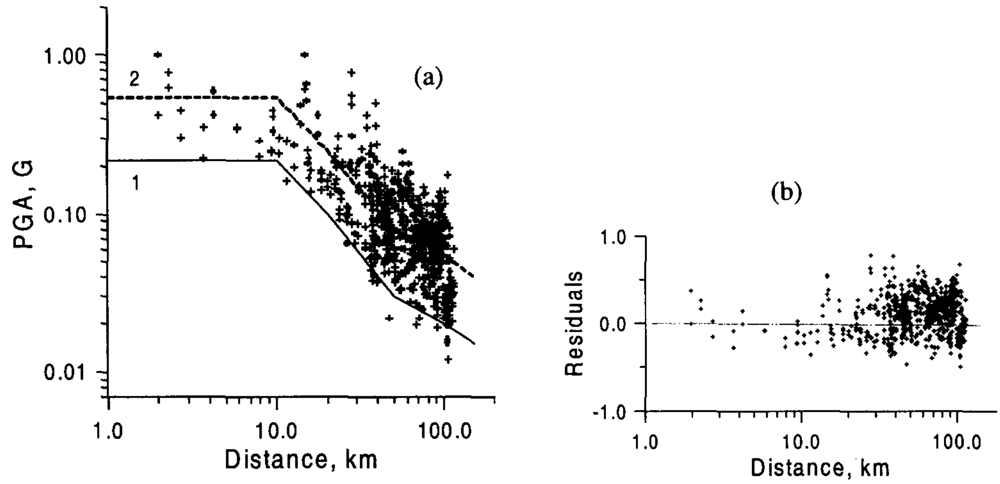

Figure 2. (a) comparison between horizontal peak ground accelerations observed during the Chi-Chi earthquake (crosses) and PGA values calculated using different spectral models (lines): 1) very hard rock (VHR) spectra; 2) "average soil" spectra. (b) residuals for peak ground acceleration as a function of distance. The residuals are defined as the ratio between observed data and PGA's predicted using "average soil" spectra.

LOCAL SITE RESPONSE

The source scaling and attenuation model described above has been used for estimation of site response characteristics in terms of frequency dependent amplification (spectral ratios) (Sokolov et al. 2000b). The approach consisted in calculating spectral ratios between spectra of actual earthquake records (horizontal components) and those modeled for a hypothetical *very hard rock* (VHR) site. Actually, these spectral ratios reflect the difference between idealized source scaling and attenuation models and real recordings. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. On the one hand, when using a large enough number of events varied by magnitude, source depth and azimuth, the effects of focal mechanism and directivity are expected to be averaged out. On the other hand, the variability of spectral ratios due to uncertainties introduced by source and propagation path effects and variability in the site response itself, may be described in terms of random variable characteristics and further used along with source scaling and attenuation models when estimating the seismic hazard. The analysis of spectral amplification functions obtained by this approach in the Caucasus area showed (Sokolov 1997, 1998a, 1998b) that the estimations are consistent with available geotechnical data (for example, thickness of soil deposits). They produce reliable prediction of ground motion parameters in the region, when used in conjunction with the corresponding source scaling and attenuation models for the hard rock.

The data set used for the site response study in the Taipei area included recordings of 66 earthquakes of M_L = 2.6-6.5 with hypocentral depths varying from 1 km to 118 km and hypocentral distances up to 150 km obtained at 35 stations located within the alluvium-filled Taipei basin. Figure 3a shows the distribution of the epicenters of earthquakes producing recordings that were used to study site response characteristics. The location of the recent Chi-Chi earthquake (M_L = 7.3, September 21, 1999) is shown in Figure 3b.

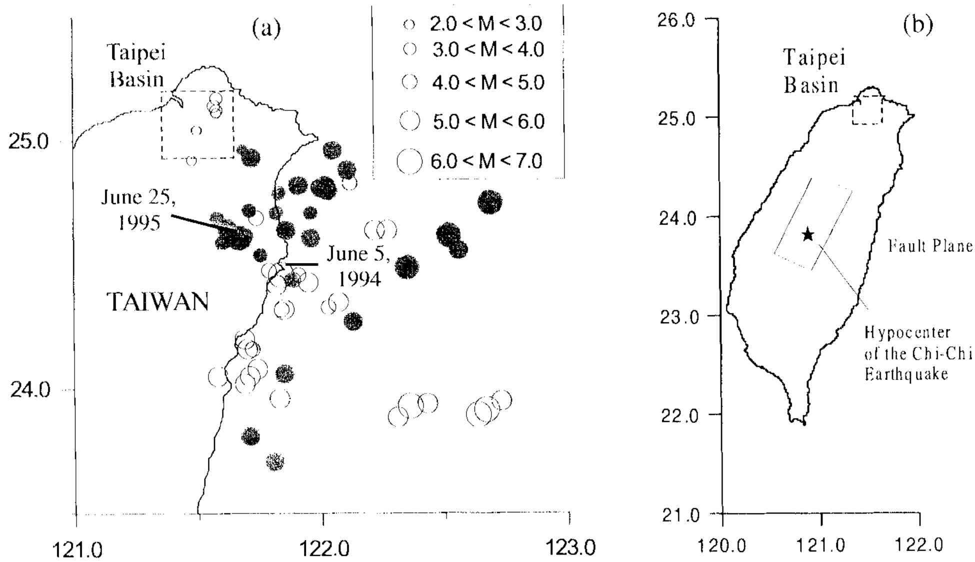

Figure 3. (a) Distribution of epicenters of the earthquake recordings that are used for study of site response characteristics in the Taipei basin. Open circles indicate shallow earthquakes (hypocentral depth $H \leq 35$ km), and shadow circles indicate deep ($H > 35$ km) events. (b) Location of the Chi-Chi (M_L=7.3) earthquake of September 21, 1999 (the source plane after Yagi and Kikuchi, Earthquake Research Institute, Univ. of Tokyo, Japan).

The Taipei basin is a triangle-shaped alluvium structure, and the area (about 240 square kilometers) is almost flat with an altitude above the sea level of less than 20 meters. The geological structure inside the basin consists of the Quaternary layers, which were separated into five stratigraphic formations, above the tertiary base rock. Figure 4 shows a scheme of the Taipei basin and the stations of Taipei strong motion observation network used. The dotted contour lines indicate the depth of the basement rock in meters. The average values of S-wave velocity change from 170 m/sec for the upper Quaternary layer, up to 650 m/sec for the deepest layer, and the base rock is characterized by an average S-velocity of 1200 m/sec.

The amplification curves (spectral ratios) were calculated for the 35 stations shown in Figure 4. Depending on the shape of the mean-amplitude spectral ratio, the sites may be divided into three categories: 1) sites that are characterized by a single prominent peak for the amplification within a relatively narrow frequency band; 2) multiple, but well-defined resonances (stations TAP09, TAP21, TAP26, TAP29, TAP30, TAP33, TAP54, TAP99); 3) broadband amplification (stations TAP05, TAP08, TAP10, TAP11, TAP24, TAP32, TAP37, TAP43). The first category, in turn, may be divided into two subcategories: 1a) he fundamental response frequency does not depend on the earthquake depth (e.g., stations TAP02, TAP03, TAP06, TAP20, TAP22, TAP27, TAP48, TAP53), and 1b) the resonance frequencies are different for deep and shallow events (TAP12, TAP13, TAP14, TAP15, TAP16, TAP38). Examples of the site amplification characteristics are shown in Figure 5. On the one hand, it is possible to conclude that the type of amplification relates to the site geology. Resonance at a single frequency occurs when there is a uniform well-defined layer over bedrock, and the influence of other layers is negligible. Multiple resonances are caused by a small numbers of well-defined layers, and broadband amplification may occur when there is a gradual increase of shear wave velocity with depth. On the other hand, uneven basement topography and complex local structure may also produce additional resonance peaks and be a source of considerable variability in the spectral ratios.

To verify the ability of the applied method to represent the amplitude and frequency dependence of site response, we used a simple 1-D technique which allows us to calculate the theoretical spectral amplification of a multilayered soil column overlying the rigid half-space for SH- and SV-waves approaching the bottom of the soil with arbitrary angles of incidence. Theoretical spectral ratios were calculated for horizontal components of motion for SH- and SV-waves using different angles of incidence. Actually, the angles for different S-wave portions may vary significantly depending on the peculiarities of the earthquake source and propagation path.

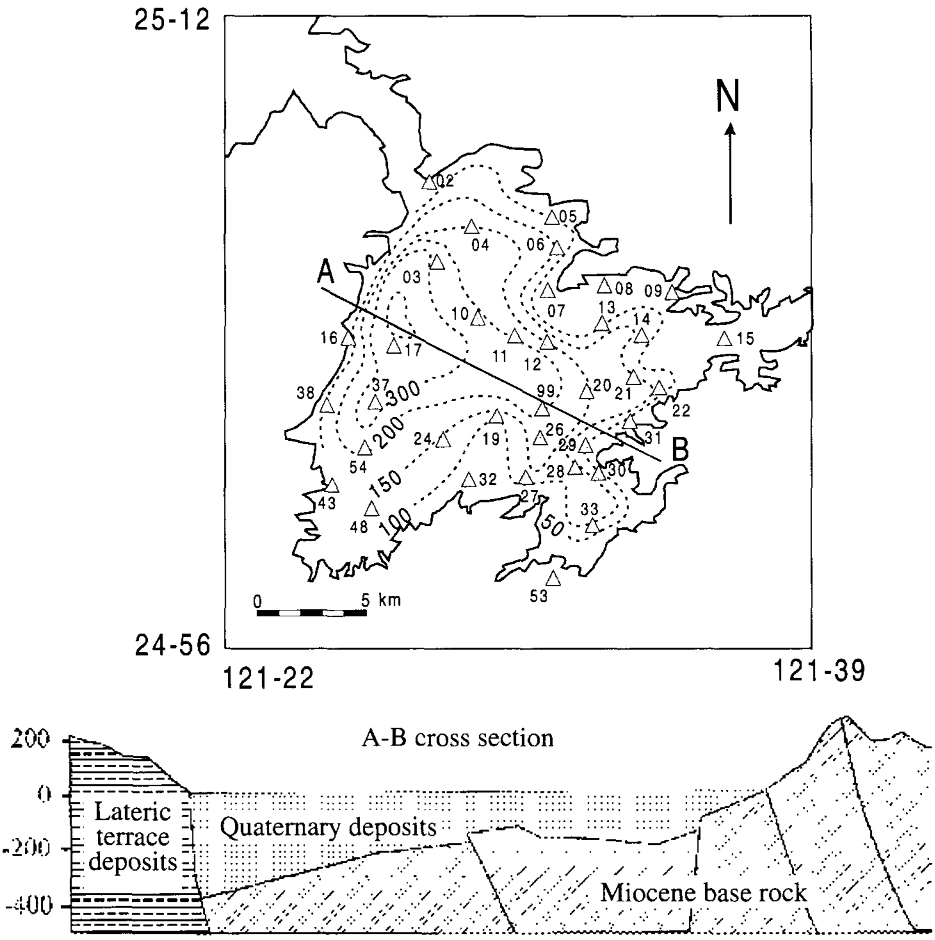

Figure 4. Map of the Taipei basin and location of TSMIP network stations (triangles), which produce the recordings used for the study of site response characteristics (Sokolov et al. 2000b). Numbers indicate the station codes. The dotted contours show the depth in meters to the base rock surface in the Taipei basin (Lee et al. 1978).

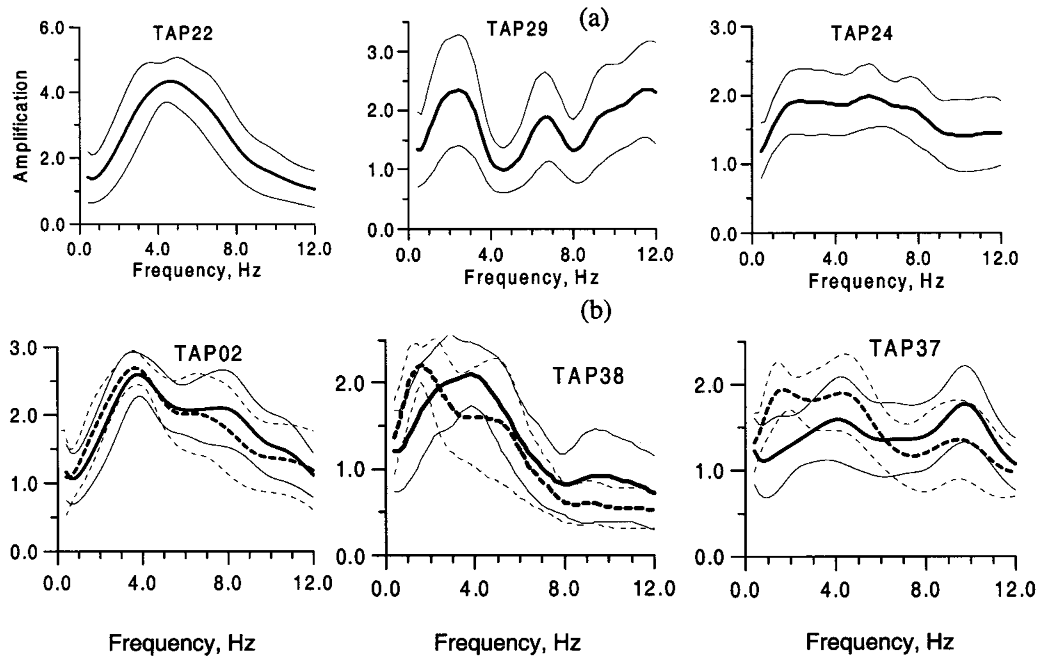

Figure 5. Characteristics of the site response amplification (examples) in the Taipei basin. (a) spectral ratios showing three categories of the site response: single resonance peak, multiple well-defined resonance and broadband amplification. The thick solid lines represent mean-amplification values; the thin solid lines show ± 1 standard deviation. (b) comparison of the site response characteristics that were determined for deep (solid lines) and shallow (dashed lines) earthquakes. The thick lines represent mean-amplification values; the thin lines show ± 1 standard deviation limits.

Figure 6 shows a comparison between theoretical spectral ratios which were obtained using 1-D models (average values for SH- and SV-waves and for six incidence angles: 10°, 20°, 30°, 40°, 50° and 60°) and empirical ratios for stations that are characterized by different thickness of Quaternary deposits and approximately the same character of site response during deep and shallow earthquakes. It is seen that multilayered models reveal good agreement with empirical data, and the theoretical curves lay within ± 1 standard deviation limits. Amplitudes on the amplification peaks depend on the impedance ratio between the basement ($V_{S1}\rho_1$) and layer ($V_{S2}\rho_2$), and the quality factor $Q(f)$ combined with the layer thickness determines the amplification at high frequencies. Most probably, the difference between amplitudes of theoretical and empirical spectral ratios is caused by discrepancy in accepted and real properties of the Quaternary deposits.

At the same time, the 1-D model fails to predict the site amplification for station TAP10, located in the deep part of the Taipei basin (see Figure 4). Empirical spectral ratios for this station and station TAP11 show "a lack" of low-frequency amplification and relatively high amplitudes at moderate frequencies as compared with the nearest stations which are characterized by approximately the same thickness of sediments (e.g., TAP03). A detailed map of the basement depth (Lee et al. 1978; see Figure 4) shows narrow crests across the valley in its southern and northern parts. It is reasonable to suppose that the influence of these crests (scattering of the seismic waves on the basement irregularities) is a source of the above mentioned peculiarities in site response for stations situated near the crest slopes. These effect are more pronounced in the central part of the basin, where the changes in basement topography are the steepest and the stations are located on the "lee side," meaning the direction from which seismic waves are propagated. The 3-D modeling is necessary to verify this suggestions.

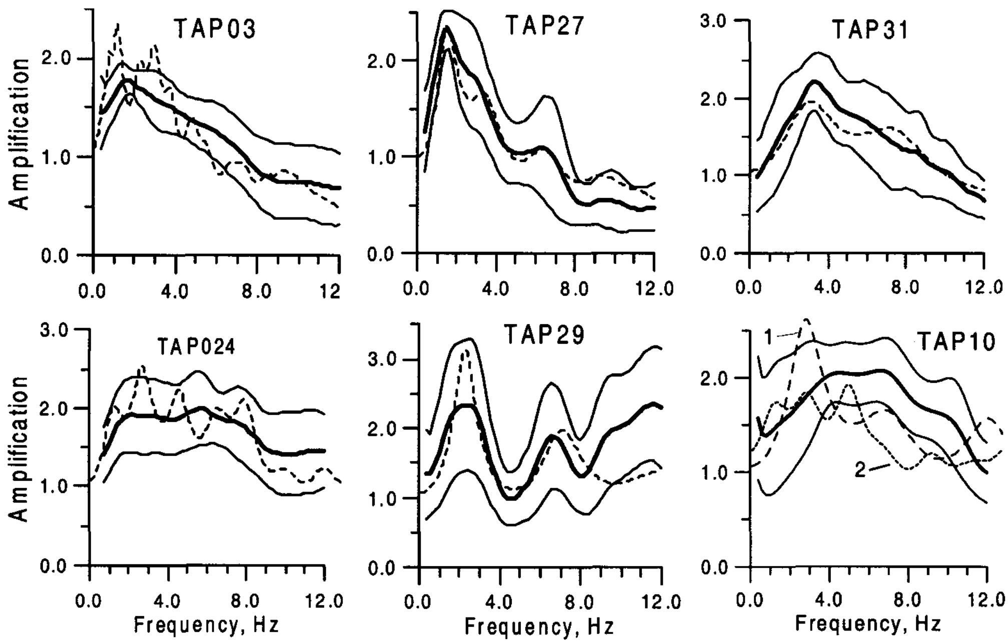

Figure 6. Comparison between empirical spectral ratios (solid lines; the thick line shows mean-amplitude values and the thin lines show ± 1 standard deviation limits) and theoretical spectral ratios (dashed lines, the average curve for SH- and SV-waves) which were calculated using 1-D models. Theoretical spectral ratios for station TAP10: 1) the model that describes the whole Quaternary deposits (5 layers); 2) the model that describes the upper formation (3 layers).

As it has been shown recently (e.g., Bard and Gariel 1986; Silva 1989; Jongmans and Campillo 1990), the 1-D model may be inadequate at high frequencies near the edge of the sediments where the sediment-basement rock interface may generate vertically propagating shear waves from the edges. In the case of the Taipei valley, the site response for the stations which are located near the basin edges may be classified as a single or multiple resonances (e.g., station TAP29, Figure 6), and it may be described by the influence of an uniform soft layer or a small number of well-defined layers over bedrock. For station TAP29, taken as an example, the amplification peak at about 2 Hz is caused by response of a soft (V_S = 200-300 m/sec, thickness 25-35 meters) layer of upper Quaternary deposits, and underlying relatively rigid (V_S = 500-600 m/sec) and thin (thickness of about 10 meters) layer causes the amplification at about 7 Hz. However, the site response for this station is also characterized by prominent amplification at frequencies more than 10 Hz which could not be explained by a simple 1-D model. It is necessary to note that station TAP29 is located near an irregularity of the basin edge and, probably, the peculiarity of site amplification for the station is an evidence of the so-called basin-edge effect.

The conclusions of the site response study in the Taipei area may be summarized as follows:

1. The spectral characteristics of the site response in the Taipei basin show that the frequency of maximum amplification peak (fundamental resonance) does not necessarily depend on the thickness of Quarternary deposits that fill the valley. The site amplification is determined by the properties of multilayered and complex structure of the deposits and the valley configuration.
2. The amplitude and shape of spectral ratios may be different for deep and shallow events. In this case, the site response characteristics for shallow events, in general, show relatively low-frequency amplification, while those for deep events also reveal prominent peaks in the high-frequency domain. The difference between averaged spectral ratios for shallow and deep earthquakes may exceed a factor of 1.5 at certain frequencies, however, their ± 1 standard deviation limits overlap each other.
3. The site response for stations located near the edge of the basin can be modeled accurately by a 1-D model using a few shallow low-impedance surface layers. A complex multilayered 1-D model is required to describe the site amplification for the stations located on the deep sediments. However, the 1-D models fail to predict spectral ratios for the sites located near subsurface topographic irregularities.

GROUND-MOTION MODELING

The stochastic simulation technique introduced by Boore (1983) was used to generate synthetic time histories of ground motion on the basis of the obtained regional spectral models and local site amplification functions. One of the most important parameters of the stochastic predictions is the duration model, because it is assumed that most (90%) of the spectral energy given by Equation 1 is spread over a duration $\tau_{0.9}$ of the accelerogram. The frequently used duration models are the following:

$$\tau_{0.9} = \tau_0 + b\,R, \tag{8}$$

where τ_0 is the source duration and bR represents a distant-dependent factor to account for dispersion (Herrmann 1985; Atkinson and Boore 1995);

$$\log_{10} \tau_{0.9} = 0.207\, M_S + 0.264 \log_{10} R - 0.65 \pm 0.19, \tag{9}$$

for rock sites, and

$$\log_{10} \tau_{0.9} = 0.178\, M_S + 0.4 \log_{10} R - 0.48 \pm 0.24, \tag{10}$$

for soft soil sites (Shteinberg 1986). Atkinson and Boore (1995) for eastern North America used the following parameters: $\tau_0 = 1/(2 f_0)$ (f_0 is the corner frequency), and b is 0.16 for $10 \le R \le 70$ km; -0.03 for $70 \le R \le 130$, and 0.04 for $R \ge 130$ km. Wen and Yeh (1991) studied strong motion duration for the Taiwan region. They obtained the following relationship for ground acceleration

$$\tau_{0.9} = 0.430\, exp\,(0.504\, M_L) \pm 2.749, \tag{11}$$

for the whole data set including alluvium site and rock site records. Unfortunately, they did not present the relationships between duration and distance, although they mentioned that the duration has a slight tendency to increase with distance up to about 80 km. It has been found in our previous study (Sokolov et al. 2000a) that Atkinson and Boore's (1995) duration model tends to overestimate peak amplitudes at small (R < 30 km) hypocentral distances, while the duration models proposed by Shteinberg (1986) and Wen and Yeh (1991) give a better fit to empirical data.

To choose the proper duration model to be used for site-dependent ground-motion stochastic modeling, peak ground acceleration (PGA) values were calculated for 28 earthquakes at station TAP22, for 16 earthquakes at station TAP37, and for 18 earthquakes at station TAP38 using recently obtained regional source scaling and attenuation models, and mean-amplitude site amplification function. The site response for station TAP22 is characterized by prominent amplification at intermediate frequencies that does not depend on the earthquake depth (see Figure 5a). The amplification function for station TAP37 reveals a broadband amplification and the response depends on the earthquake depth. The site response for station TAP38 also depends on the earthquake depth, however, it reveals a prominent peak for the amplification within a relatively narrow frequency band (Figure 5b). Figure 7 shows distribution of residuals Δ between modeled A_M and registered A_R (both horizontal components) maximum amplitudes $\Delta = \log_{10}A_R - \log_{10}A_M$. It is seen that Shteinberg's duration model for soil sites (Equation 10) yields to underestimation of maximum amplitudes for earthquakes of M > 5, or for distant events: in considered case most of the earthquakes of M > 5.0 occurred at distances more than 40 km. For this case the mean residual (model bias) is 0.09 with standard deviation 0.19. At the same time, PGA values obtained using Wen and Yeh's duration model that doesn't depend on the distance (Equation 11) show good agreement with empirical data. For this case the mean residual is 0.02 with standard deviation 0.15. Therefore, the Wen and Yeh's duration model which provided practically no bias, was chosen as the most suitable for stochastic simulation in Taiwan area

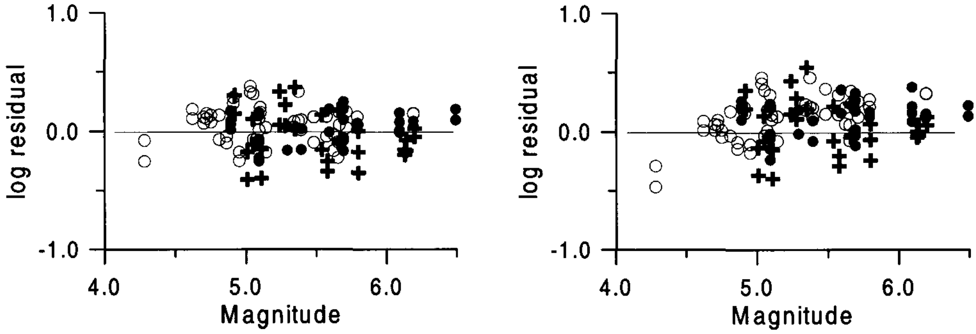

Figure 7. Residuals for stations TAP22 (open circles), TAP37 (black circles) and TAP38 (crosses) as a function of magnitude M. The residual are defined as the difference between $\log_{10} A_R$ and $\log_{10} A_M$, where A_R and A_M are recorded and modeled maximum acceleration, respectively. (a) Wen and Yeh's (1991) duration model; (b) Shteinberg's (1986) duration model.

Until 1999 two strong earthquakes had been registered by many stations located within the Taipei basin, namely, event of June 5, 1994, M_L = 6.2, hypocentral depth H = 5 km, and event of June 25, 1995, M_L = 6.5, hypocentral depth H = 40 km (see Figure 3a). Many strong motion records were also collected during the M_L = 7.3, September 21, 1999 Chi-Chi earthquake (Figure 3b). Thus, it is possible to test the applicability of the obtained models by comparison of the modeled and observed data. We calculated the PGA values for the stations that have been triggered by these events using the VHR spectral model and the site amplification functions. Figure 8 shows comparison between the distribution of observed (averaged values from two horizontal components) and estimated maximum accelerations. It is seen that PGA values calculated for the M_L = 6.2 and M_L = 6.5 events show a good agreement with observed data and they reflect the dependence of maximum amplitudes of ground acceleration on the recording site characteristics (position relative to the basin edge, depth of the sediments, etc.). However, the distributions of theoretical and observed PGA's for the Chi-Chi earthquake reveal several differences. The scheme of observed PGA distribution along the Taipei basin during the Chi-Chi earthquake reveals high acceleration values in the northern and northwestern parts of the basin. The theoretical modeling does not predict high PGA's for these parts of the area. Most probably, the peculiarity of the PGA distribution is caused by the influence of azimuthal direction of incident excitation on the basin response. The local site response in the Taipei basin, except for a few small events, was studied using the records from earthquakes were located to the Southeast of the basin (Figure 3a). The obtained site amplification functions, working well in the case of southeastern earthquakes, may be unsuitable for some parts of the basin in the case of large shallow earthquakes that occur in the central part of the island. An analysis of the Chi-Chi earthquake aftershock data, as well as 3-D modeling, is necessary to verify the suggestion.

To verify the ability of the considered models to predict "site- and region-specific" response spectra, we compared simulated and observed 5% damped response spectra for typical site conditions, namely, a) deep Quaternary deposits (thickness more than 200 meters), station TAP03, event of 5 June, 1994; b) Quaternary deposits of intermediate thickness (about 150-200 meters), station TAP12 for events of 5 June, 1994 and 25 June, 1995; shallow deposits (thickness less than 50 meters), station TAP48 for event of 5 June, 1994 and station TAP53 for the event of 25 June, 1995 (Figure 9 and 10). The simulated spectra essentially fit the observed data for the considered site condition. Figure 11 shows comparison of the spectra simulated for different stations and, therefore, for different local site conditions. The spectra estimated for the hypothetical "very hard rock" site are shown in Figure 11 also. It is seen that response spectra at shallow soft soil (stations TAP48 and TAP53) are characterized by the largest high-frequency amplitudes, that exceeds 2-3 times those for "hard rock sites" or for station TAP03 (deep deposits). At the same time, the level of high-frequency part of the spectra decreases with increasing of the thickness of Quaternary deposits (stations TAP48 [TAP53]-TAP12-TAP03).

To provide a quantitative measure of the accuracy of ground motion estimation using the models, we estimate statistical characteristics of the residual Δ between modeled R_M and registered R_R (both horizontal components) response spectra ($\Delta = \log_{10}R_R - \log_{10}R_M$). For this purpose, 28 earthquakes registered at station TAP22, 16 earthquakes at station TAP37, and 18 earthquakes at station TAP38 were used. Figure 12 shows the model bias (e.g., average residuals) along with ± 1 standard deviation. The results show little or no bias from low periods up to 1 sec. For periods larger than 1 sec, the observed spectra are, on average, larger than the simulated ones due to noise of the records (Sokolov et al. 2000a). The standard deviation does not exceed 0.3 log unit (average value 0.25) for the considered periods.

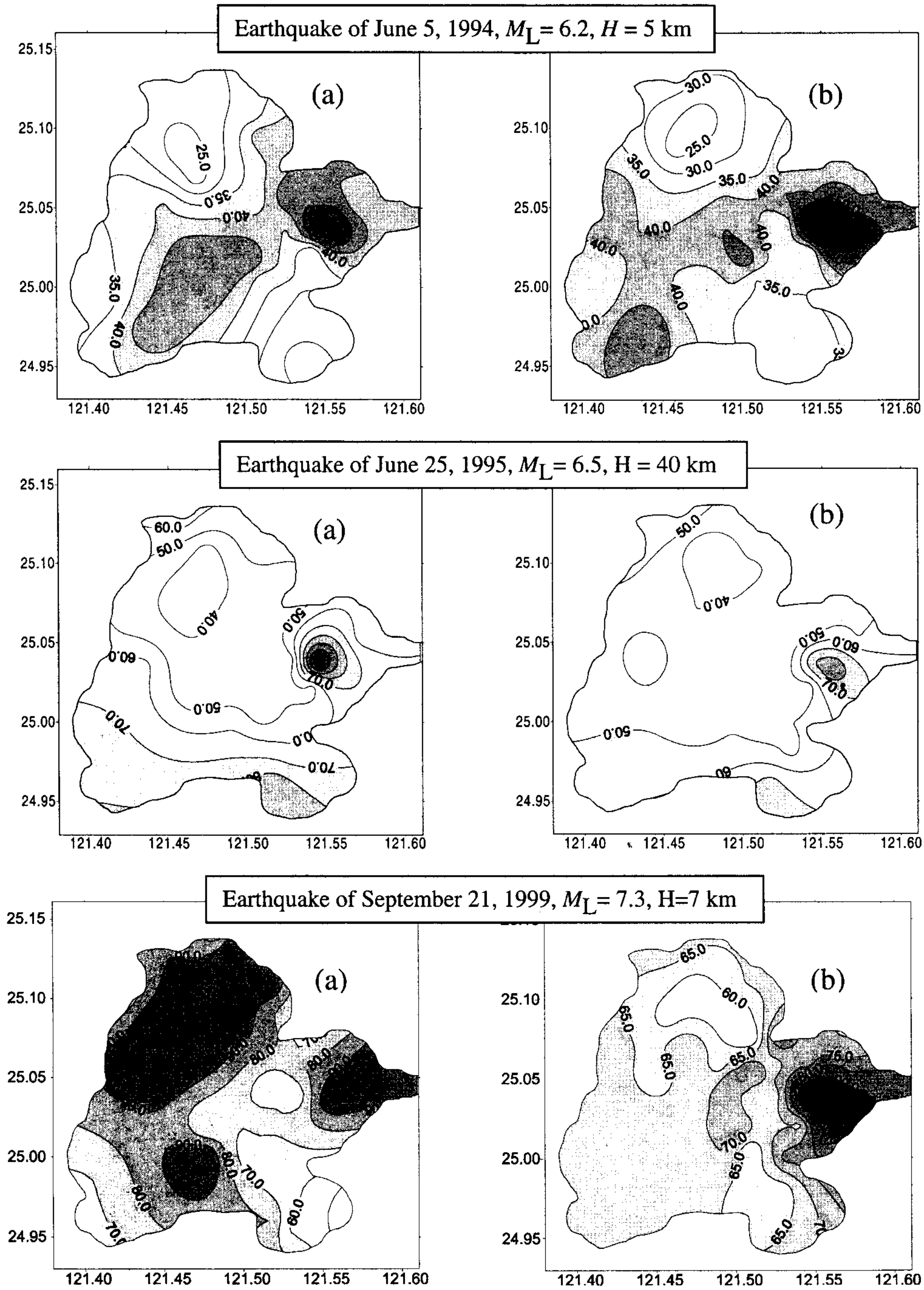

Figure 8. Comparison of the PGA distribution for large earthquakes: (a) real earthquake data; (b) results of the stochastic simulation) along the Taipei basin. The simulated PGA values were obtained using the regional spectral models for very hard rock site and empirical site amplification functions.

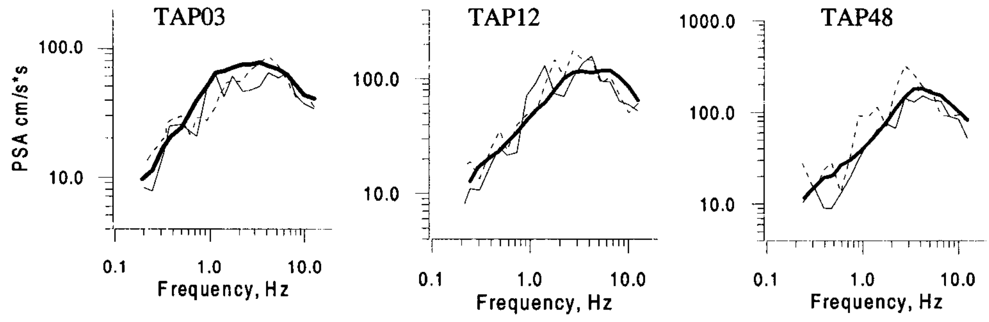

Figure 9. Comparison of 5% damped response spectra (thin lines, solid and dashed lines denote N-S and E-W components, respectively) and simulated spectra (thick line, averaged from 40 simulations) for event of June 5, 1994, $M_L = 6.2$.

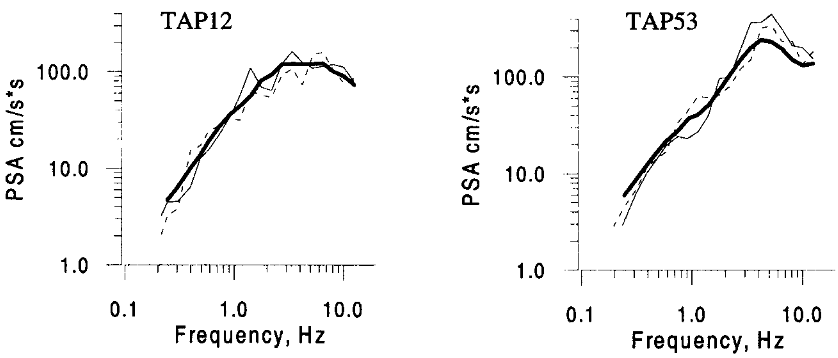

Figure 10. Comparison of 5% damped response spectra (thin lines, solid and dashed lines denote N-S and E-W components, respectively) and simulated spectra (thick line, averaged from 40 simulations) for event of June 25, 1995, $M_L = 6.5$.

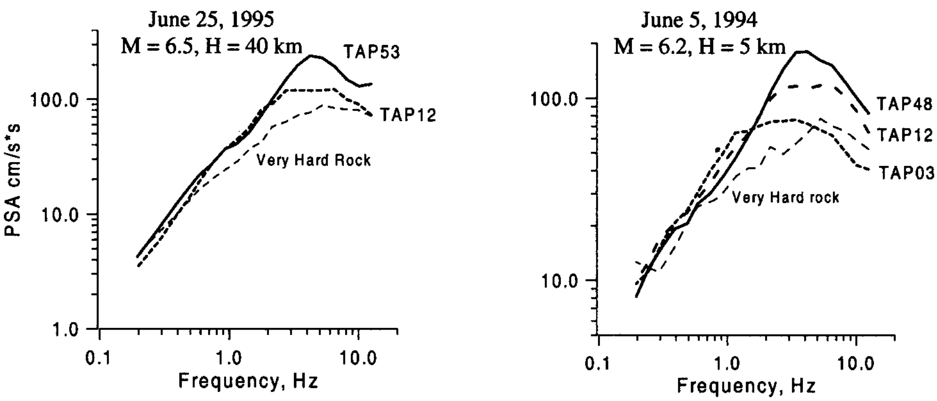

Figure 11. Comparison of 5% damped response spectra simulated for different site conditions: hypothetical "very hard rock"; shallow soft soil (TAP48 and TAP53); Quaternary deposits with thickness about of 150-200 m (TAP12) and more than 200 m (TAP03).

CONCLUSIONS

We used stochastic modeling technique to calculate peak round accelerations and response spectra for Taipei area. The source, path and site effects were characterized separately on the basis of the analysis of a large collection of ground-motion recordings obtained since 1991 in Taiwan area. The simple ω-squared Brune's point-source model combined with regional anelastic attenuation (Q) and duration ($\tau_{0.9}$) models provides a satisfactory estimation of ground-motion parameters for rock sites. The parameters of the source spectral model (seismic moment M_0 and stress parameter $\Delta\sigma$) for a modeled earthquake should be estimated using regional relationships between M_0, $\Delta\sigma$ and magnitude M_L. Effects of local site response are considered by means of empirical soil/bedrock spectral ratios calculated as ratios between spectra of actual earthquake records and those modeled for a hypothetical "hard rock" site. Actually, these spectral ratios show the difference between idealized source scaling and attenuation models and real recordings. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. Therefore, the variability of the empirical amplification functions reflect regional peculiarities of seismic waves excitation and propagation, as well as intrinsic variability in the site response itself (by virtue of different incidence angles, lateral soil heterogeneity, etc.).

The results of the simulation demonstrate that this combination of source, path and site response models provides an accurate prediction of "site- and region-dependent" ground-motion parameters for the Taipei basin for a broad range of earthquake magnitudes, distances and site conditions. The standard deviation of variance between the observed and computed ground motion parameters does not exceed 0.2 log unit for maximum accelerations and 0.3 log unit for 5% damped response spectra. The "average soil" model, in general, provides a satisfactory prediction for the case of the recent $M_L = 7.3$ Chi-Chi earthquake. The average value of the residuals (model bias) is about 0.028, and the standard deviation is about 0.22 log unit. The models, with a set of generic soil profiles, can be considered as an efficient tool for estimating of design input ground motion parameters in the Taipei basin both in deterministic (scenario earthquakes) and probabilistic ("site- and region-dependent" Uniform Hazard response spectra) seismic hazard assessment. At the same time, the model has an ability to be improved when more data became available (analysis of the spectral ratios variability with respect the earthquake source depth and azimuthal direction of incident excitation, and detailed study the site response in low frequency (below 1 Hz) domain).

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