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Site Effect Evaluation Using Combination of Source Scaling Models and Ground Motion Records

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SITE EFFECT EVALUATION USING COMBINATION OF SOURCE SCALING MODELS AND GROUND MOTION RECORDS

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ABSTRACT

We analyze site response of the Taipei basin using the records obtained by the Taiwan Strong Ground Motion Instrumentation Program (TSMIP) network. Records of 66 earthquakes of M=2.6-6.5 with a hypocentral depth varying from 1 km to 118 km and hypocentral distances of up to 150 km are studied for 35 stations located within this triangle shaped alluvium structure. The site response is obtained in terms of spectral ratios calculated by dividing of the site spectrum by the reference spectrum estimated for a hypothetical "very hard rock" site. The recently developed empirical source scaling and attenuation models are used for the reference spectra calculation. This approach allows us to evaluate the variability of spectral ratios due to uncertainties introduced by source and propagation path effects and variability in the site response itself. The characteristics of site response in the Taipei basin depend on the properties of soil deposits and, in general, may be described by 1-D models. However, there are some peculiarities of spectral ratios that show the influence of subsurface topography.

KEYWORDS

Local site response, spectral ratios, non-reference site technique

INTRODUCTION

It is well understood that near-surface geological conditions strongly influence earthquake ground motion at a particular site, and the building codes used in earthquake-prone countries take into account the effect of local site conditions by using simplified site categories. Recent destructive earthquakes including the 1985 Michoacan earthquake in Mexico, the 1988 Spitak earthquake in Armenia, the 1989 Loma Prieta and the 1994 Northridge earthquakes in California, and the 1997 Hyogo-Ken Nanbu (Kobe) earthquake in Japan reveal the necessity to re-evaluate the building code provisions because the earthquakes were more severe that the provisions allowed for. It is believed that local site effect is one of the major factors controlling the damage during these events. Among many factors determining the site response to earthquake ground motion the influence of laterally irregular geological structures - sediment-filled valley or basin - may play a key role in site amplification and damage distribution (e.g., Irikura et al., 1996).

Obviously, the best way to investigate the peculiarities of the influence of local geology on seismic motion is to analyze the records obtained during various earthquakes. Empirical studies of sediment-filled valley response became available with an increasing in the earthquake recordings and the establishment of dense arrays. Various site response estimation techniques using S-wave windows have already been developed and studied. The most common procedure (Borcherdt, 1970) is to determine the sediment-to-bedrock ratio by dividing the spectrum of a site by that of a nearby reference (rock) site using earthquake records. Alternative methods not requiring a reference site have been developed recently, and several studies were devoted to comparison and testing of these techniques (e.g., Field and Jacob, 1995; Riepl et al., 1998).

Recent needs of earthquake engineering require local soil effect to be included in probabilistic seismic hazard analysis. The characteristics of site response used in seismic hazard calculation should reflect the variability of the response depending on the source parameters and propagation path peculiarities. In addition, it should be possible to use them in conjunction with an accepted strong ground motion attenuation model to produce realistic estimates. An approach, that seems to satisfy these requirements, and which could allow us to keep the advantages of traditional spectral ratio technique and to use every record of every earthquake, has been proposed recently (Sokolov, 1998). It consists of calculating the spectral ratio between the spectra of actual earthquake records 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 the effects of source rupture peculiarities and inhomogeneous propagation path. On the one hand, when using a large enough number of events, which vary in 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 seismic hazard.

We used the technique to study the seismic response of the Taipei basin. The large number of ground motion acceleration recordings, obtained during the execution of the Taiwan Strong Motion Instrumentation Program (TSMIP) since 1991 (Kuo et al., 1995), provide an opportunity to study both regional source scaling and attenuation models for the Taiwan region, as well as local characteristics of soil response in the Taipei basin where more than forty stations are currently in operation. The purpose of this work is to study the variation of local site effect in different parts of the sediment-filled valley - the Taipei basin - during earthquakes, which vary in magnitude, focal depth, and distance. The spectral amplification curves were obtained for the sites within Taipei basin at frequencies of engineering interest ($0.4 \leq f \leq 12$ Hz), using the records obtained from 66 earthquakes ($2.8 \leq M \leq 6.5$) with hypocentral distances of up to 150 km. The reliability of the site amplification data is estimated by comparison with the results of 1-D mathematical modeling. This work also may be considered as a study of the effectiveness of the methodology.

GEOLOGICAL STRUCTURE OF THE TAIPEI BASIN

The Taipei basin is a triangular alluvium structure, and the area (about 240 square kilometers) is almost flat at an altitude above the sea level of less than 20 meters. The geological structure inside the basin consists of Quaternary layers above tertiary base rock. Figure 1 shows a scheme of the Taipei basin, a cross section through the basin, and stations of the Taipei strong motion observation network whose recordings are used in this study. The stratigraphic formations of the Quaternary layers are, in descending order, surface soil, the Sungshan Formation, the Chingmei Formation, and the Hsinchuang Formation. The Sungshan Formation is composed mainly of alternating beds of silty clay and silty sand, and covers almost the whole Taipei basin. The Chingmei Formation is a fanshaped body of conglomerate deposits. The Hsinchuang Formation, recently separated into the Wuku and Panchiao Formations, consists of bluish gray and clayey sand with some conglomerate beds. The average P- and S-wave velocity structures for the Taipei basin are given in Table 1 .

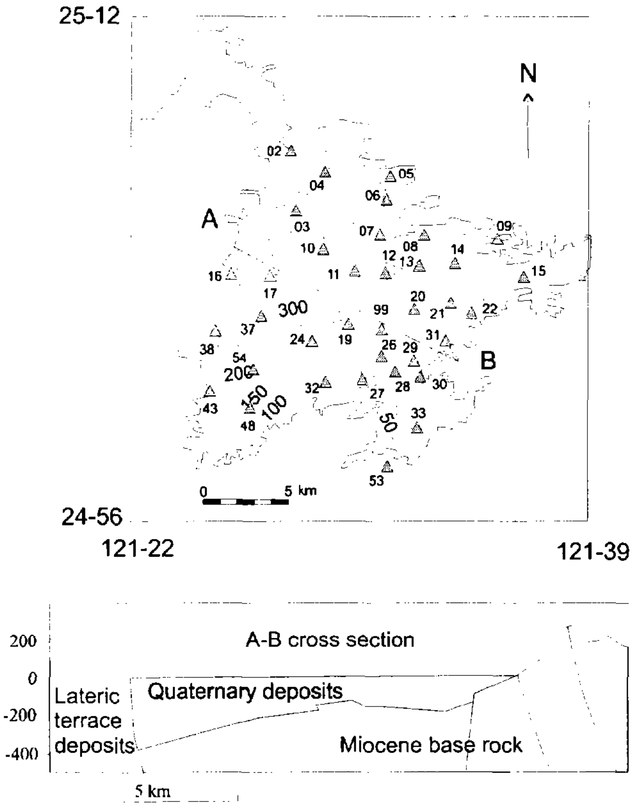

Fig. 1. Map of the Taipei basin and location of the TSMIP network stations (triangles) recordings of which were used in this study. Numbers indicate the station codes. The dotted contours show the depth in meters to the base rock surface in the Taipei basin.

Table 1. Velocity structure of the Taipei basin

Formation	Location		V_P (m/sec)	V_S (m/sec)
	Northwestern part of the basin	Southwestern part of the basin		
Sungshan	0-20	0-15	450	170
	20-50	15-35	1500	230
	50-100	35-50	1600	340
Chingmei	100-160	50-100	1800	450
Wuku	160-320	100-200	2000	600
Panchiao	320-400	200-250	2200	650
Basement			3000	1200

METHOD OF ANALYSIS AND THE DATA PROCESSING

The site/bedrock spectral ratios (SBSR) are obtained by dividing the actual spectrum by the reference spectrum, which is modeled for a hypothetical "very hard rock" (VHR) site. The advantages to this technique are as follows. In the traditional spectral ratio method, the choice of reference site may be very difficult: the reference site should be located on a hard rock outcrop not far from the sedimentary site, and it should provide records of almost every earthquake. However, a regionally appropriate source scaling and attenuation model for "hard rock" site is usually available or may be derived on the basis of earthquake recordings. The use of the model makes it possible to analyze all records. The SBSR functions reflect an intrinsic variability in the site response itself (by virtue of different incidence angles, back-azimuths etc.) and the source and path effects. The results in conjunction with "very hard rock" spectral model could be incorporated into "site-dependent" seismic hazard assessment. The empirical ω-squared model for the Taiwan region has recently been developed (Sokolov et al., 2000) on the basis of 1380 acceleration records obtained during 176 earthquakes ($4.5 \le M \le 6.5$) which occurred since 1991 at distances of up to 200 km. The model was used for the determination of reference spectra.

The general model of radiated spectra for "very hard rock" site, describing the Fourier acceleration spectrum A at frequency f, can be expressed in the following way (Boore, 1983)

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

where C is the scaling factor, $S(f)$ is the source spectrum, $D(R,f)$ is the diminution function, $I(f)$ represents frequency-dependent site response. The scaling factor is given by

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

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 β are the density and shear velocity in the source region, respectively, b is the coefficient of geometrical spreading model, and R is the hypocentral distance. A commonly used source function $S(f)$ in the Brune's (1970) model is

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

For the Brune 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 approximately 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 $f_{\max}$. 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

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

where $P(f, f_{\max})$ is a high-cut filter.

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

$$\log_{10} M_0 = 19.043 + 0.914\, M_L \qquad (5)$$

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

$$\log_{10} \Delta\sigma = -3.3976 + 0.2292 \log_{10} M_0 \pm 0.61 \qquad (6)$$

The frequency-dependent attenuation of spectral amplitudes with distance may be described using quality factor $Q = 225 f^{1.1}$ for deep earthquakes and $Q = 125 f^{0.8}$ for shallow events.

Processing of the records consisted of visual inspection of every accelerogram, selection of the significant part of the record starting from S-wave arrival, and the computation of Fourier amplitude spectra of the horizontal components using a 10% cosine window. The spectra were smoothed using a three-point running Hanning average filter (twenty consecutive smoothings were applied for raw spectra to reveal gross features of site amplification). Seismic moment (M_0) and stress parameter ($\Delta\sigma$) estimations are not available for almost all the earthquakes under consideration, therefore we used regional relationships (Eqs. 5 and 6) for preliminary evaluation of average values. The comparison of empirical spectra, and modeled reference "very hard rock" spectra is shown in Fig. 2. Station TAP53 is situated outside the Taipei basin (see Fig. 1) on shallow layer of soft soil. Station TAP12 is situated in the center of the basin, and thickness of Quarternary deposits in this part of the valley is about of 200 meters. The empirical spectra reveal distinct amplification when compared with reference ones at frequencies 4-6 Hz for station TAP53 and 1-3 Hz for station TAP12.

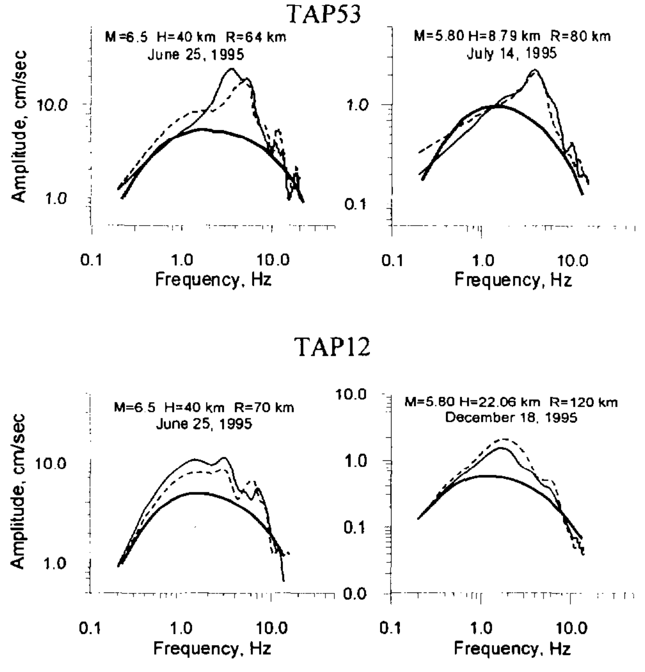

Fig. 2. Comparison of smoothed observed spectra (thin lines, solid lines - NS component, dashed lines - EW component) and reference "very hard rock" modeled spectra (thick lines) for the earthquakes of magnitude M, hypocentral depth H and hypocentral distance R .

The signal-to-noise ratio allows us to analyze the spectra at frequencies from 0.8 Hz to 12-14 Hz for all the records. To minimize the uncertainties introduced by the choice of stress parameter to be used for reference spectra estimation, the spectral ratios were normalized assuming their maximum amplitude. This approach, however, requires scaling of the normalized spectral ratios to estimate absolute amplitudes of the amplification. Generally, spectral ratios should approach unity at very low frequencies, and therefore the "basic value" of every SBSR function may be obtained by extrapolating its average curve to $f \sim 0.0$ Hz. On the other hand, theoretical modeling using available geotechnical information may be applied for scaling.

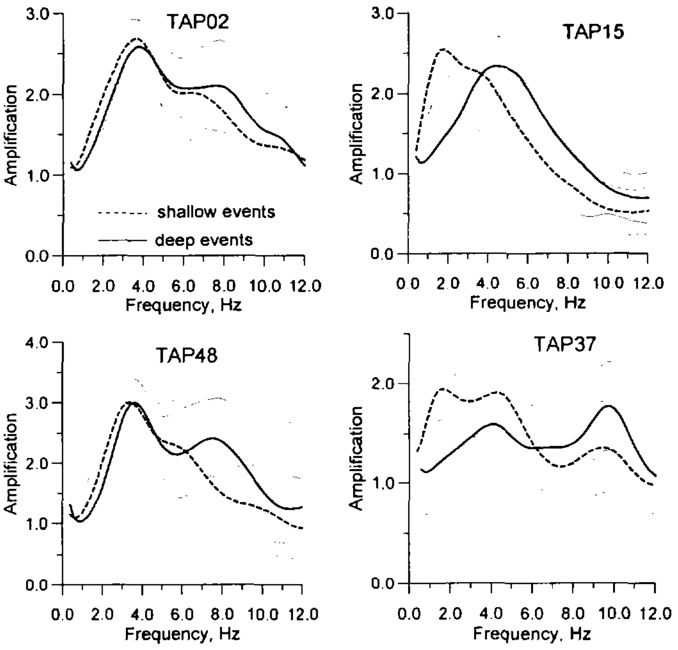

Fig. 3. Comparison of the site response characteristics, which were determined for deep (solid lines), and shallow (dashed lines) earthquakes. The thick lines represent mean-amplification values; the thin lines show ± 1 standard deviation limits.

RESULTS AND DISCUSSION

We determined the site amplification at 35 stations of TSMIP network (see Fig. 1) and, when it was possible, the spectral ratios were calculated separately for deep and shallow earthquakes. Figure 3 shows the characteristic of site response – mean amplitude values and ± 1 standard deviation limits. It has been found that for several stations the difference between amplification curves for deep and shallow events may exceed a factor of 1.5. These stations are characterized by a shift of fundamental resonance peak to higher frequencies for deep earthquakes as compared with this for shallow events. A special study showed that the observed difference is intrinsic feature of the sites, and it is caused by a combination of site, source and propagation path effect.

Depending on the shape of the mean-amplitude spectral ratios, the sites may be divided into three categories: 1 - the sites that are characterized by a single prominent peak for the amplification within a relatively narrow frequency band; 2 - multiple, but well defined resonanses; 3 - broadband amplification. The first category, in turn, may be divided into two subcategories: a - the fundamental response frequency does not depend on the earthquake depth, and b - the resonance frequencies are different for deep and shallow events. 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 an 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 the depth. On the other hand, uneven basement topography and complex local structure may also produce the additional resonance peaks and be a source of the considerable variability in the spectral ratios.

The stations, which are characterized by broadband amplification, are located within the area stretched from SW to NE direction along the western and central parts of the valley. In contrast, the stations showing a single peak of spectral amplification are situated in the eastern part and near the edge of the Taipei basin. A map of the basement depth 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.

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 multi-layer soil column overlying the rigid halfspace 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 and appropriate parameters for the soil column models (number of layers, thickness, shear velocity, density and attenuation). Figure 4 shows a comparison between theoretical spectral ratios obtained using 1-D models (average values for SH- and SV-waves and for six incidence angles: 10^0, 20^0, 30^0, 40^0, 50^0 and 60^0) and empirical ratios for stations, which are characterized by different thickness of Quaternary deposits and approximately the same character of the site response during deep and shallow earthquakes. It is seen that multi-layered models reveal good agreement with the empirical data, and the theoretical curves lay within ± 1 standard deviation limits.

At the same time, the 1-D model fails to predict site amplification for station TAP10 located in the deep part of the Taipei basin. Empirical spectral ratios for this station and nearby station TAP11 show "a lack" of low-frequency amplification and relatively high amplitudes at moderate frequencies as compared with the other nearest stations which are characterized by approximately the same thickness of sediments. It is reasonably to suppose that the scattering of the seismic waves on the basement irregularities is a source of the above mentioned peculiarities in the site response. This effect could be seen 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.

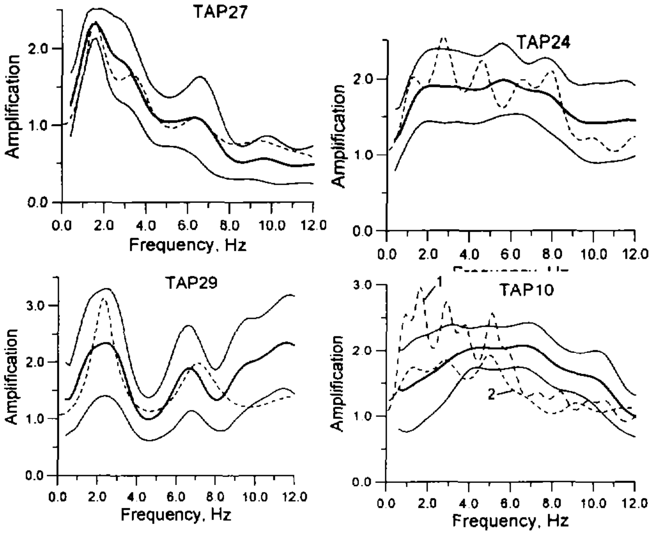

Fig. 4. Comparison between the empirical spectral ratios (solid lines; thick line shows mean-amplitude values and thin lines show ± 1 standard deviation limits) and theoretical spectral ratios (dashed lines, average curve for SH- and SV-waves) which were calculated using 1-D models. Theoretical spectral ratios for station TAP10: 1 – model described the whole Quaternary deposits (5 layers); 2 – model described the upper Sungshan formation (3 layers).

Since the Taipei basin may be considered as a wide shallow alluvial valley (depth/length ratio less than 0.25), it is interesting to study so-called "basin effect" — the peculiarities of the response should depend on the site location relatively the basin edge. The sediment-basement rock interface may generate vertically propagating shear waves from the edges. Therefore, as it has been shown recently (e.g., Jongmans and Campillo, 1990), the 1-D model may be inadequate at high frequencies near the edge of the sediments. 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), 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 frequency of about 2 Hz is caused by response of a soft (V_S=200-300 m/sec, thickness 25-35 meters) layer of Shungshan formation, and relatively rigid (V_S=500-600 m/sec) and thin (thickness of about 10 meters) layer of Chingmei formation causes the amplification at frequency of about 7 Hz. However, the site response for station TAP29 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 the station is located near an irregularity of the basin edge (see Fig. 1). In general, it is possible to conclude that, for the most stations, there is no clear evidence of the "basin-edge effect" at least at frequencies up to 10-12 Hz, and the 1-D model can be used for calculation of the site amplification in the Taipei basin in the frequency range from 0.4-0.5 to 10-12 Hz.

CONCLUSION

In this study we used a modification of the spectral ratio method based on the calculation of frequency response at each station with respect to a hypothetical *very hard rock* (VHR) site. The method allows us to estimate site amplifications from all the recordings even though there is no reference rock station available. The reference VHR spectra are obtained using source scaling and attenuation models, which were recently established for Taiwan region. This approach also allows us both to estimate the influence of source and propagation path effects on the site response and, when using large enough numbers of earthquakes, to evaluate the variability of spectral ratios that is important for probabilistic assessment of seismic hazard.

Recordings from 66 earthquakes obtained at 35 stations in the TSMIP network in the Taipei area were used in this study. The magnitude range is from 2.6 to 6.5 on the local magnitude scale, focal depth is between 1 km and 118 km, and the hypocentral distance range is from 10-15 km to 150-160 km. Horizontal-component site-amplification data were obtained within the frequency interval 0.4 Hz to 12 Hz. The ensemble averages of the site response estimation are consistent with theoretical modeling of the amplification curves both in amplitude, resonance frequencies and overall shape. The conclusions may be summarized as follows:

1. The method of S-wave site response estimation relative to a regional spectral model for hypothetical "very hard rock" site has been found capable of providing the reliable estimations of site amplification at locations where a nearby reference site is not available. The use of the method to analyze the recordings of the TSMIP network provides us with an opportunity to study the peculiarities of the site response in the Taipei sedimentary basin. The results in conjunction with "very hard rock" spectral model may be used for "site-dependent" seismic hazard assessment.

2. 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, which fill the valley. The site amplification is determined by the properties of multilayered and complex structure of the deposits and the valley configuration.

3. The amplitude and shape of spectral ratios may be different for deep and shallow earthquakes. 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.

4. The site response for the 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 multilayer 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.

Of course, there are some unresolved problems. To validate the proposed method, we used one-dimensional models whose parameters were estimated independently. To check the results thoroughly, it seems to be useful also to use the other non-reference-site-dependent techniques such as the inversion scheme introduced by Boatwright et al. (1991), as well as the 2-D and 3-D modeling. The comparison of the predicted and empirical strong motion data should also allow to verify the model. As can be seen from Figure 3, the local site response in the Taipei basin, except a few small earthquakes that are located directly under the basin, was studied using the records from earthquakes which occurred in 1993-1998 and located to the Southeast of the basin. The influence of azimuthal direction of incident excitation on the response of the Taipei basin should be studied on the basis of the data obtained recently during the strong Chi-Chi earthquake of September 21, 1999 (M_L=7.3) and its aftershocks. These earthquakes occurred to the South and Southwest of the basin (in the center of Taiwan island), and provides an unique set of TSMIP recordings.

In this paper we do not consider peculiarities of the site response with respect to the direction of the records components. This analysis, as well as the detailed study of the spectral ratio variability with respect to the earthquake source depth, requires inclusion of more earthquake recordings from the stations under consideration and for collection of the data from other stations located within (and in the vicinity) of the Taipei basin. At the same time it is necessary to study the site response in the low frequency domain (below 1 Hz). These are the topics for future research.

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