The microzonation of Seismic design earthquake for Taipei Basin

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ABSTRACT :

Taiwan is located at the convergent plate boundary where the Eurasian plate has been eastward underthrusting and colliding with the Philippine Sea plate. This tectonic environment results in high seismicity in and around the Taiwan Island. Undoubtedly, earthquake hazard mitigation is an important issue in Taiwan. It is worthy of noting that Taipei City, the capital of Taiwan and located on a sediment-filled basin, has experienced several damaging earthquakes in which the most recent event occurred on March 31, 2002. Obviously, even the earthquake located more than 80-100 km away, it still cause the severe damage in the Taipei Basin due to the site or basin effect. The essential way to mitigate the earthquake hazard is to refine the current seismic design code by a more a proper definition of seismic demands for different site conditions so that the undesired damage of structures due to earthquake excitations can be efficiently prevented. The CWB has installed a very dense ground-motion array in the Taipei Basin. The earthquake data collected in the last decades was used to investigate the local site effects on the ground shaking in the Taipei Basin. Based on the attenuation relationship modified by the records of reference sites to eliminate the source and path effects by events, the site effect of each TSMIP station was studied and quantified by an amplification factor to the reference site (hard site). Applying the ground motion amplification factors with more detailed information on site conditions can remove bias and reduce the uncertainly of ground motion estimates from the attenuation relationship. Finally, performing the probabilistic seismic hazard analyses with the proposed site amplification factors, the more proper microzonation of the Taipei basin can be proposed for the current seismic design code.

KEYWORDS: microzonation, seismic design code, basin, amplification factor, site effect

1. INTRODUCTION

Taiwan is located at the convergent plate boundary where the Eurasian plate has been eastward underthrusting and colliding with the Philippine Sea plate at a rate of about 70 to 80 *mm/yr*. This tectonic environment results in high seismicity in and around the Taiwan Island. The statistics shows that more than 7,780 people were died due to the damaging earthquakes in the last century (Cheng *et al.*, 1999). In addition, the majority of the catastrophic earthquake events such as the 1999 Chi-Chi earthquake occurred at the western area of Taiwan, which is the higher populated area. Therefore, the seismic damage potential in and around Taipei City should be paid more attentions since not only it is the capital of Taiwan with the densest population but also it is located on the Taipei Basin which is a sediment-filled basin. The previous researches indicate that even if the earthquakes have mostly occurred outside the basin, the thick recent deposits in the "soft" basin have caused the significant damage due to the site amplifications (Wang *et al.*, 2004). Apparently, during the 1999 Chi-Chi earthquake (M_L7.3; epicenter 150*km* to the south) and the 2002 Hualien earthquake (M_L6.8; epicenter 100*km* to the southeast), although the epicenter is sufficiently distant from the Taipei Basin, which is usually referred to the "far-field earthquake", it was observed that many buildings still collapsed severely within the Taipei Basin. It is evident that the site effect plays an important role in the seismic damage potential especially for the basin topography. As a consequence, the corresponding proper seismic demands at different site conditions within the Taipei Basin in the up-to-date seismic design code are necessary to be further studied in order to efficiently mitigate the probable earthquake hazard.

Taiwan supported an extensive seismic instrumentation program, which operated by the CWB for the populated areas with dense digital strong-motion networks. This instrumentation program consists of two networks around Taiwan: (1) The Taiwan Rapid Earthquake Information Release System (TREIRS, also known as the Real-Time Digital stream output system, RTD); and (2) The Taiwan Strong Motion Instrumentation Program (TSMIP). The RTD system using a real-time strong-motion accelerograph network consisting more than 80 stations is currently capable of routine broadcasting of the earthquake location and its magnitude about one minute after the occurrence of an earthquake (Wu *et al.*, 2002). The TSMIP system, composed of more than 700 stations that are spaced approximately 5 km apart in populated areas, is widely deployed in Taiwan area. Accordingly, a large amount of the high quality earthquake data collected by the network of TSMIP can be used in this study to more deeply investigate the site amplification effect on the Taipei Basin in response to different levels of excitation.

Due to the fact that the seismic microzonation within the Taipei Basin in the current seismic design code was determined based on the earthquake data recorded by the limited stations from 1993 to 1999, i.e., the 1999 Chi-Chi earthquake record is excluded, this paper aims at modifying the current seismic microzonation using the more intact earthquake records including sufficient damaging earthquakes. The local site effect on the Taipei Basin can be discussed as follows:

1. The parameter C_v , the spectral acceleration at 1 second spectral period, for defining the site-dependent normalized design response spectrum can be determined based on the average response spectrum of the observed strong ground motions at each observation station within the Taipei Basin and the surrounding areas (Yeh *et al*, 2001).

2. The attenuation relationship should be modified by the records of reference sites (rock sites) in the Taipei Basin to eliminate the source and path effects by different earthquake events, and the modified attenuation relationship is then adopted to evaluate the site effect for each TSMIP station within the Taipei Basin in terms of a corresponding amplification factor.

Performing the probabilistic seismic hazard analysis with either of the aforementioned information, a modified seismic microzonation within the Taipei Basin can be established. The proposed seismic microzonation within the Taipei Basin considering the more intact earthquake records is more applicable compared with the current one in the seismic design code.

2. GEOLOGIC BACKGROUND OF TAIPEI BASIN

The Taipei Basin is triangular in shape with an area of about $20km\times20km$. Four young formations are found sitting flat above the basement which is at most $700m$ deep. The Taipei Basin is considered to be structure forming in origin. From the Pliocene to the Pleistocene age, three reverse and NE-SW trend faults developed in this area along the western Taiwan foothills. From NW to SE, they are the Hsinchuang fault, the Kanchiao fault and the Taipei fault. About 400 thousand years ago, the tectonic pattern in northern Taiwan changed and the area was “flipped” to become a tensile environment. One of the reverse faults, i.e., the Hsinchuang fault, altered its sense of movement and became a normal fault, now called the Sanchiao fault, which caused the Taipei Basin to sink. This tectonic expansion could have been induced by a pure tension, which caused the basin to assume its triangular shape. Thus, the deepest part of the basin is along the NW border, where the Sanchiao fault is located. This one-sided subsidence made the basin’s Tertiary basement in a half-graben shape (Figure 1). Four newly deposited unconsolidated strata were overlying the basement (Figure 1). Of these, the middle Chingmei Formation is mainly composed of gravels. It separates the overlying silt-dominated Sungshan Formation and the underlying sand-and-silt Wuku Formation and the gravel-rich Banchiao Formation. Their ages are 400 (Banchiao), 250 (Wuku), 100 (Chingmei), and 30 (Sungshan) thousand years (Ka), respectively. The top near-surface layer, called the Sungshan Formation, is thought to carry the burden of the site-effects because of its loose sand and silt content (Wang *et al.*, 2004).

Due to the aforementioned geologic conditions, the basin effects of the Taipei Basin are more complicated then those of the other sites with the soft soil condition. A theoretical 3D model may be developed to study the amplifications of ground motions due to the basin effects. Alternatively, an empirical procedure must be developed based on the recorded earthquake data to estimate the basin effects.

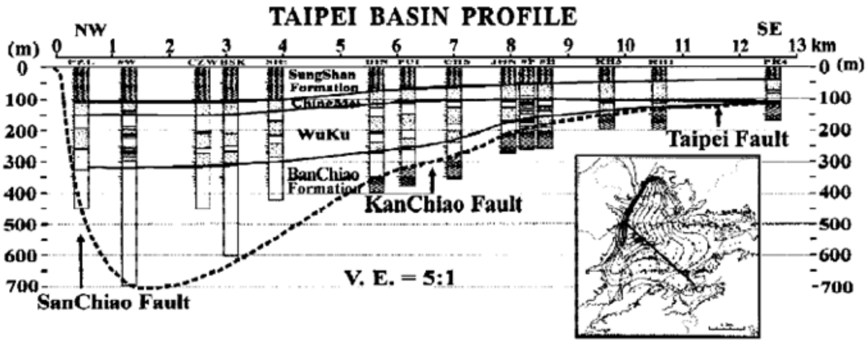


Figure 1 A profile across the Taipei basin perpendicular to the strikes of the faults. (Wang *et al*., 2004)

3. CURRENT SEISMIC DESIGN CODE FOR TAIPEI BASIN

For the current seismic design code for buildings in Taiwan, the elastic seismic demand is represented by the design spectral response acceleration S_{aD} corresponding to a uniform seismic hazard level of 10% probability of exceedance within 50 years. Due to the basin effects, the corner periods noted in the response spectra associated with the earthquake data observed in the Taipei Basin are generally larger than 1.0 second (Yeh *et al*., 2001). It implies that the parameters S_{DS} and S_{D1} prescribed in the design response spectrum for general sites can not be applied directly for sites in the Taipei Basin. Alternatively, it is based on the parameters of C=2.5 and $C=C_v/T$ for the normalized design response spectrum within the short and moderate period ranges, respectively. The parameter C_v and the associated corner period ($T_0=C_v/2.5$) can be determined from the observed strong ground motions for each observation station within the Taipei Basin. Then, based on the contours of parameter C_v and the boundaries of the municipal units, four seismic micro-zones are defined in the Taipei Basin. The representative values of corner period T_0 between short and moderate period ranges of the design response spectrum are prescribed as shown in Table 1. In addition, utilizing the uniform hazard analysis, the design spectral response acceleration S_{aD} for a given site can be developed directly from the design spectral response acceleration at short periods S_{DS} (S_{DS}=0.6g) as well as the corner period T_0 for each seismic micro-zone in the Taipei Basin. It can be expressed as:

$$S_{aD}=\begin{cases} S_{DS}\left(0.4+3T/T_0\right) & ;\quad T\le 0.2T_0 \\ S_{DS} & ;\quad 0.2T_0<T\le T_0 \\ S_{DS}T_0/T & ;\quad T_0<T\le 2.5T_0 \\ 0.4S_{DS} & ;\quad T>2.5T_0 \end{cases} \tag{3.1}$$

The distribution of the four micro-zones and the shapes of the corresponding design response spectrum in Taipei Basin are shown in Figure 2. It is found that the microzonation map of the corner period is in accordance to the basin shape and reflects the thickness of the sedimentary soil layers in the Taipei Basin.

Table 1 Representative values of corner period for each micro-zone in Taipei Basin

Micro-zone	Taipei Zone 1	Taipei Zone 2	Taipei Zone 3	Taipei Zone 4
Range of C_v	3.6 – 4.6	2.8 – 3.6	2.2 – 2.8	1.5 – 2.2
T_0 or T_0^M (sec.)	1.60	1.30	1.05	0.85

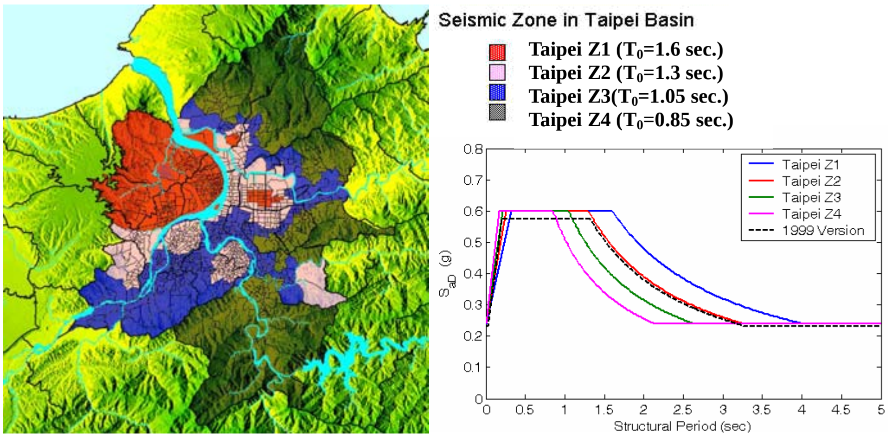


Figure 2 Distribution and the design response spectrum for each microzonation in the Taipei Basin (Yeh *et al.*, 2001)

4. EARTHQUAKE DATABASE

4.1. Criteria for Database

Among the earthquake events occurred from 1991 to 2007, ninety-three earthquake events with the magnitude of greater than M_L5.0 were selected. From those ninety-three selected earthquake events, 1914 earthquake histories with PGA of greater than 10*gal* recorded by 120 stations of the TSMIP network within and around the Taipei Basin were adopted in the desired analysis database. Figure 3 shows the locations of 120 stations and seismicity within and around the Taipei Basin. Besides, the locations of the epicenters of those 93 selected earthquake events are depicted in Figure 4, from which the main shock and five large aftershocks of the 1999 Chi-Chi earthquake are also observed. Obviously, using the extensive analysis database instead of the previous one is capable of determining the more adequate distribution of parameter C_v for the Taipei Basin.

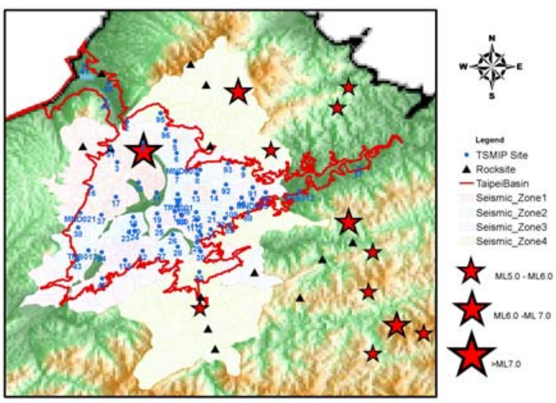


Figure 3 Distribution of the strong motion array in the Taipei Basin.

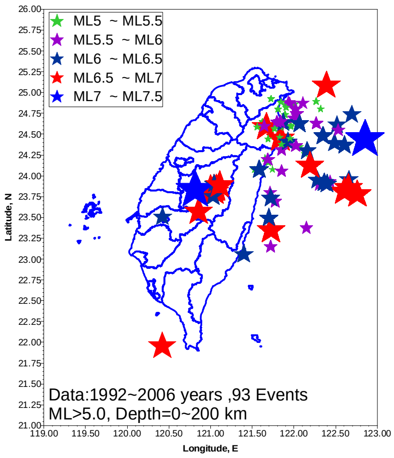


Figure 4 The locations of epicenter of 93 selected earthquake events

4.2. Controlling Earthquakes

The seismic demands specified in the design code were determined based on the seismic hazard analysis, which is usually to develop rock outcrop or hard site ground motion for seismic design and earthquake loss estimation. This procedure, for determining the controlling earthquakes and developing a seismic hazard information base, is based on a de-aggregation of the probabilistic seismic hazard in terms of earthquake magnitudes and distances. The seismic hazard information base summarizes the contribution of individual magnitude and distance ranges to the seismic hazard and the magnitude and distance values of the controlling earthquakes at the 10% probability of exceedance within 50 years level of the Taipei Basin. The hazard contributions corresponding to the various magnitudes and distances (or each sub-source) in the Taipei Basin are shown in Figure 5. Comparing to the seismicity and zoning scheme, it is concluded that these controlling earthquakes locate in subduction zone of NE part of Taiwan. The distances and magnitudes of these controlling earthquakes are greater than 70*km* and M_L6.8, respectively. It is found that the basin effect is significant especially when the controlling earthquake is a major, shallow and far-field earthquake such as the 1999 Chi-Chi earthquake (M_L7.3) and the 2002 Hualien earthquake (M_L6.8).

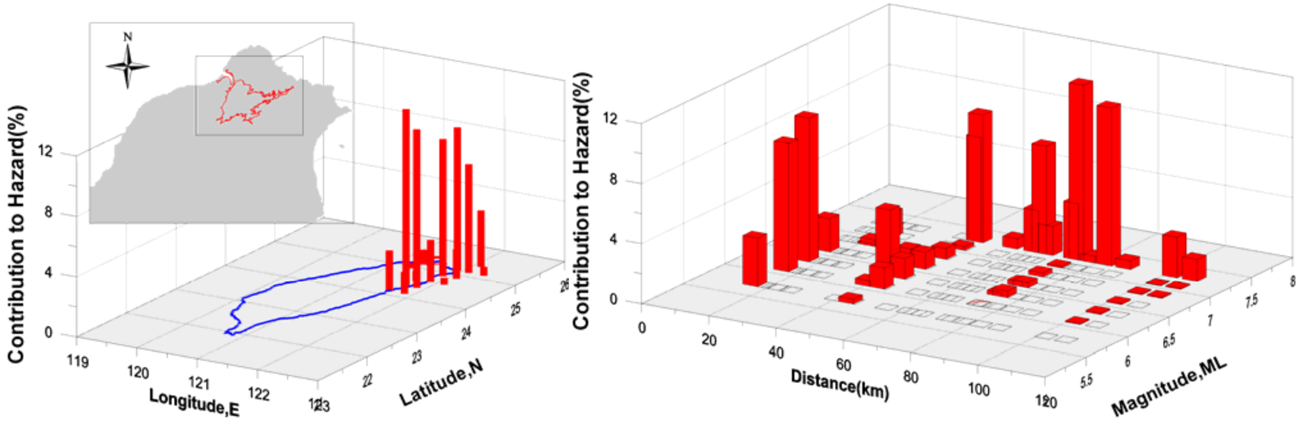


Figure 5 Distribution of hazard contribution in the Taipei Basin

5. MICROZONATION MAP OF TAIPEI BASIN

5.1. The site-dependent normalized design response spectrum, C_v

The parameter C_v, the spectral acceleration at 1 second spectral period for defining the site-dependent normalized design response spectrum can be determined based on the average response spectrum of the observed strong ground motions at each observation station within the Taipei Basin and the surrounding areas. The earthquake data selected using the McGuire relationship (McGuire, 1975) was adopted to determine the seismic microzonation within the Taipei Basin in the current seismic design code, as described briefly in the following. Once the magnitude and distance are obtained, V/A and AD/V^2 values for any earthquake history recorded by each station can be approximately estimated using the McGuire relationship. In which A, V and D represent the recorded maximum ground acceleration, velocity and displacement responses, respectively. Accordingly, the earthquake records with a larger V/A value in each station are selected for the calculation of the parameter C_v.

It is still believed that the distribution of the parameter C_v obtained from the earthquake records selected based on the McGuire relationship is not capable of revealing the realistic characteristics of the basin effect due to the consideration that there are insufficient damaging earthquake records such as the 1999 Chi-Chi earthquake. Therefore, the current seismic microzonation is necessary to be modified based on the more intact earthquake records, i.e., plenty of damaging earthquake records. In addition, ten observed strong ground motions with a larger V/A value in each station are selected to re-calculate the average normalized response spectrum and the corresponding parameter C_v.

In Figure 6, the modified distribution of the parameter C_v proposed in this study (denoted as a line contour) and the seismic microzonation specified in the current seismic design code (denoted as a fill contour) are illustrated in Figure 6 for easer comparison in the Taipei Basin. It is fond that the modified distribution is in accordance to the basin shape and reflects the thickness of the sedimentary soil layers (Figure 1) much better compared with the current seismic microzonation. It is also evident that the basin effect can be well depicted using the modified distribution of the parameter C_v considering the damaging earthquakes rather than using the current one (Chiou *et al.*, 2007).

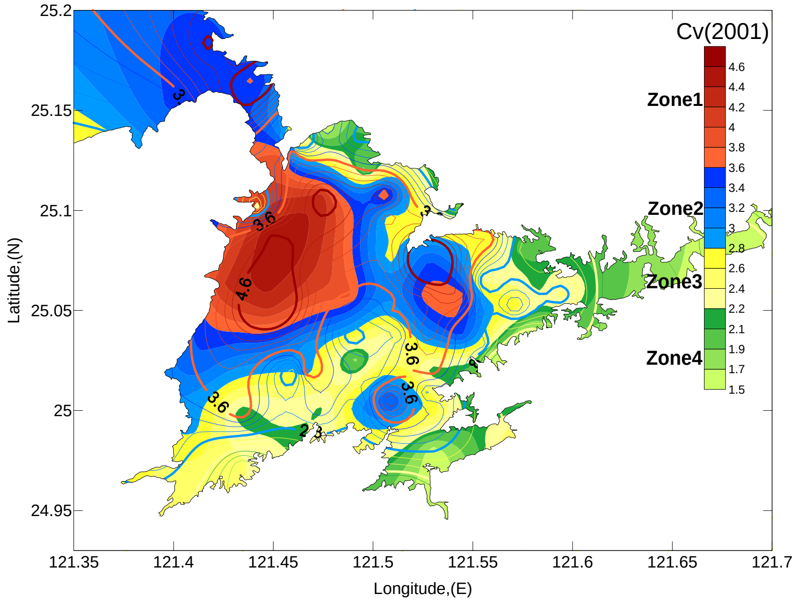


Figure 6 Distribution of the parameter C_v in the Taipei Basin

5.2. Site amplification factor

Two most important perspectives on the ground-motion and the site effects have been addresses (Field *et al.*, 2000) as follows: (1) in a single earthquake the ground shaking at one site can easily be 10 times stronger than that at a neighboring site; (2) there are two important geologic factors, the softness of the rock or soil near the surface as well as the thickness of the sediments above hard bedrock, can significantly affect the level of ground shaking. For an individual earthquake, the intensity predicted by the attenuation model may not be adequate. Based on the earthquake data collected from the TSMIP network, it is easy to find that the pattern of shaking varies from earthquake to earthquake, especially for some basins or soft soil plane areas (Jean and Loh, 2001). This discrepancy may be come from the source effect as well as the topographical and path effects.

The spectral ratio analysis of strong-motion records is a commonly used procedure to estimate the site effects in moderate to high seismicity area. Appling the concepts of spectral ratio analysis for site effects analysis of earthquake motions with respect to reference sites, the ground motion $A_{ij}(f)$ at the i^{th} site due to the j^{th} event can be expressed as

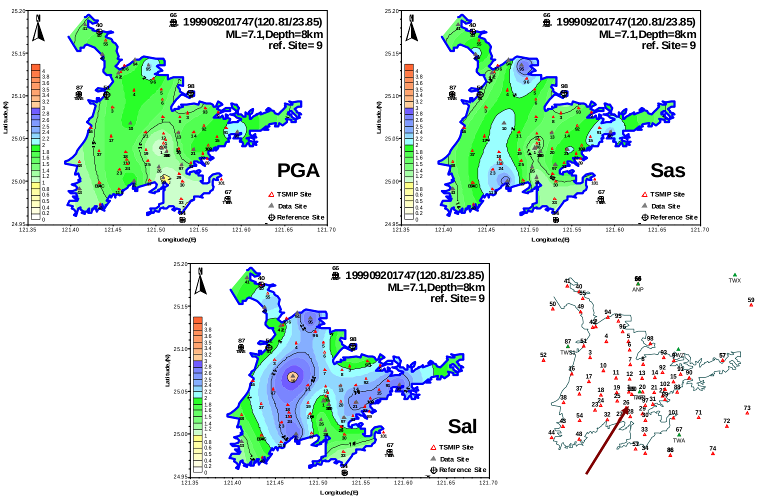
$$A_{ij}(f) = I_i(f) \cdot P_{ij}(f) \cdot S_j(f) \tag{5.1}$$

where $S_j(f)$ is the source effect; $P_{ij}(f)$ is the path effect; $I_i(f)$ is the local site effect. The ground motion model presented in Eq. (5.1) should also be applied to the reference sites. Two important criteria should be followed in the selection of reference sites: (1) the reference site locates on a hard rock nearby the study site, and, (2) the reference site has a comparable epicentral distance from the study site. However, it is very difficult to find a reference site that properly follows the two important criteria mentioned above. A ground motion prediction model for the reference site was developed to study the site effects. Based on the rock site attenuation model (Jean *et al.*, 2006), the residue analysis of the earthquake data of the selected reference site station was modified to eliminate the source, path and topographical effects by different events. The ground motion of the reference site $A_{rj}(f)$ was calculated by this modified attenuation law for all the study sites. The site amplification factor $F_{ij}(f)$ is defined as

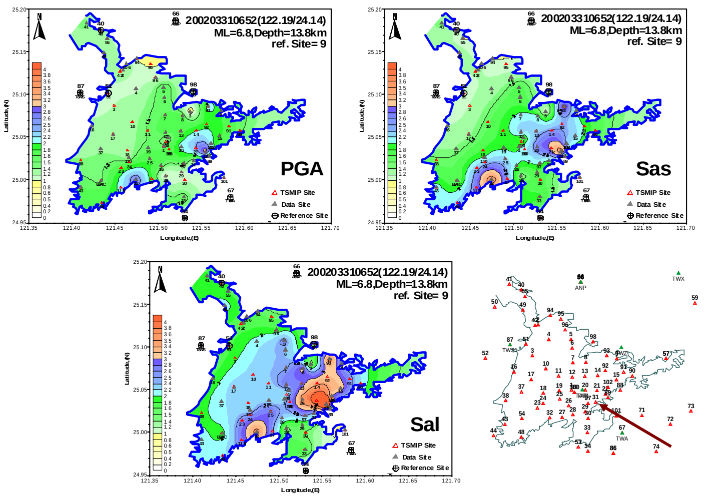
$$F_{ij}(f) = \frac{A_{ij}(f)}{A_{rj}(f)} \cong I_i(f) \tag{5.2}$$

Therefore, the distribution of the site amplification factor is estimated in Eq. (5.2). The statistical analysis of site amplification factors was performed for each site in the Taipei Basin, and then the microzonation map was generated. The seismic demands for a particular site can be obtained by multiplying the site amplification factor and the design earthquake, which was generated by hazard analysis for structural seismic design and earthquake loss estimation.

In order to have a better insight on the site amplification factors, Figure 7 shows the distributions of site amplification factors with respect to PGA, spectral acceleration response at period of 0.3 seconds and spectral acceleration response at period of 1.0 second. It is found that the various patterns are probably resulted by the different distributions of the soil velocity structure as well as different depths of the surface soil layer during the different earthquake events such as 1999 Chi-Chi earthquake and 2002 Hualien earthquake, as illustrated in Figures 7(a) and 7(b), respectively. As a consequence, a study of the averaged site amplification factor considering the various patterns should also be performed for the generation of a more adequate microzonation map in the Taipei Basin.



(a) 1999 Chi-Chi earthquake



(b) 2002 Hualien earthquake

Figure 7 Distribution of site amplification factors in the Taipei Basin under

6. CONCLUSIONS

The basin effect is not negligible in particular when the controlling earthquake is a major, shallow and far-field earthquake such as the 1999 Chi-Chi earthquake or the 2002 Hualien earthquake. In addition, since the seismic microzonation within the Taipei Basin in the current seismic design code was determined using the earthquake data recorded by the limited stations before 1999, the current seismic microzonation is needed to be modified using the more intact earthquake records including the sufficient damaging earthquakes. The analytical results show that the modified seismic microzonation is in accordance with the basin shape and the thickness of the sedimentary soil layers much better compared with the current seismic microzonation. It is also evident that the basin effect can be well depicted using the modified distribution of parameter C_v considering plenty of the damaging earthquakes. On the other hand, the residue analysis of the earthquake data of the selected reference site station was modified based on the attenuation model for rock sites to eliminate the source, path and topographical effects due to different earthquake events. After the statistical analysis of site amplification factors was performed for each site in the Taipei Basin, the microzonation map was generated. The seismic demands for a particular site can be obtained by multiplying the site amplification factor and the design earthquake that is generated by hazard analysis for structural seismic design and earthquake loss estimation.

ACKNOWLEDGEMENTS

This study is partially supported by Taiwan Science Council (NSC) under Gant No. NSC96-2625-Z-492-006. Immense gratitude is conveyed to CWB in Taiwan for the great support of rich earthquake data in TSMIP network to this study.

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