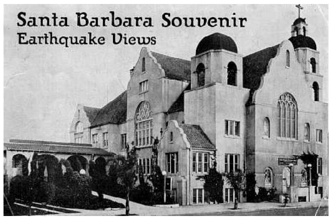

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BOREHOLE DATA AND SITE AMPLIFICATIONS IN THE TAIPEI METROPOLITAN AREA

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ABSTRACT

There are 18 boreholes inside the Taipei Metropolitan Area (TMA), which is on and around the Taipei Basin. Among them, 7 boreholes are located outside but near the TMA. The core samples of the 18 sites show that geological materials below them belong to the Sungshan formation, which is a soft layer and composes of unconsolidated sand, silt and clay. The depths of the 18 boreholes range from 30 to 56 m. The majority of the boreholes have a depth of 30 m. The depths of 2 boreholes at a Class-C site and a Class-E one are greater than 40 m. The shear velocities and densities were measured at each borehole. The shear velocity was measured every 0.5 m. The total number of samples of shear-velocity loggings is 1126 and the measured values are in the range 93 – 1235 m/s. Except for few sites, the velocity range is smaller inside than outside the basin. Inside the basin, except for sites 09 and 22, the maximum velocity is less than 500 m/s. The maximum velocity is larger to the east than to the west of the basin. Among the 18 sites, there is a Class-B site, 6 Class-C sites, 10 Class-D sites, and a Class-E site. The Class-B and C stations sites are located at the mountains outside the Taipei Basin, while the Class-C and D ones inside the basin. The density was measured only at one point in a certain geological layer. The total number of logging samples of densities is 308 and the measured values are in the range 1.3 – 2.3 gm/cc. At some well-logging points, where the shear-velocity was measured, yet lack of density, the density measured at a nearby one, which belongs to the same geological layer as the former, is assigned. A complete well-logging profile including the two parameters can, thus, be constructed at each borehole site. Based on the well-logged data, the frequent-dependent site amplifications, A[f(z)], are evaluated. Results show that at a unique Class-B site, A[f(z)] first decreases and then increases with increasing frequency, and the value varies from 15 to 1.6. At the Class-E site, A[f(z)] first increases and then decreases with increasing frequency, with a peak almost at f=5 Hz. At the Class-C and D sites, except for the data point with f>100 Hz, the amplification–frequency functions first increase with frequency, and then become flat when f>10 Hz.

INTRODUCTION

The Taipei Metropolitan Area (TMA) is located on the Taipei Basin (Figure 1a) and the political, economic, and cultural center of Taiwan. Although seismicity is lower in the area than others in Taiwan, there were still numerous earthquakes occurring near the area and caused damage (Hsu 1961; Hsu 1983a,b). In the area, pre-1970 large distant earthquakes did not cause remarkable damages, while several post-1970 seismic events occurred (Wang 1998). Observations show that the predominant frequencies of seismic waves in the Taipei Basin generated by distant earthquakes are 0.5–1.0 Hz (Chen 2003). This would result in large damage on the buildings with 10–20 floors. Before 1970, there were buildings with only few floors, usually less than 4, and, thus, the damage was small. Since 1970 a large number of high-rise buildings with 10–20 floors or more have been constructed, and, thus, the earthquake-induced damage increases, even though the quality of construction has been substantially upgraded. Meanwhile, the population has remarkably increased, a rapid transportation system has been in operation, and two nuclear power plants located in the vicinity of the area have been operated for a long time. Hence, much attention for seismic risk mitigation must be paid in the area. One of the important issues to mitigate seismic risk is the evaluation of site effect.

Several groups of researchers (Wen et al., 1995a,b; Wen and Peng, 1998; Sokolov et al., 2000, 2001; Lee et al., 2001; Sokolov and Jean, 2002; Chen, 2003; Zhang, 2004; Fletcher and Wen, 2005; Huang et al., 2009) studied the characteristics of site effects on strong ground motions in the Taipei Basin. From surficial geology, Lee et al. (2001) classified 708 free-field strong-motion station sites in Taiwan into four categories, i.e. classes B, C, D, and E, using a scheme compatible with the 1997 Uniform Building Code (UBC) provisions. However, Huang et al. (2005, 2007, 2009) addressed that the re-classification for numerous station sites is needed as taking the well-logging data into account.

Conventionally, several ways are applied to evaluate the site amplifications. One of the ways is the comparison between observed ground motions and calculated values on the basis of the velocity model assuming 1-D wave propagation (Haskell 1960; Joyner et al. 1981; Boore and Joyner 1997; Klimis et al. 1999; Huang et al. 2005, 2007, 2009). The comprehensive velocity and density models are necessary for using this method.

From well-logging data of shear velocities and densities at sites of strong ground motion stations operated by the Central Weather Bureau (CWB), Huang et al. (2009) evaluated the absolute frequency-dependent site amplifications from shallow sediments at the 18 boreholes in the Taipei Basin using the method proposed by Boore and Joyner (1997). They also estimated are the averaged frequency-dependent site amplifications from the results of individual boreholes. In this work, the well-logged data, method, and some results are reviewed based on Huang et al. (2009).

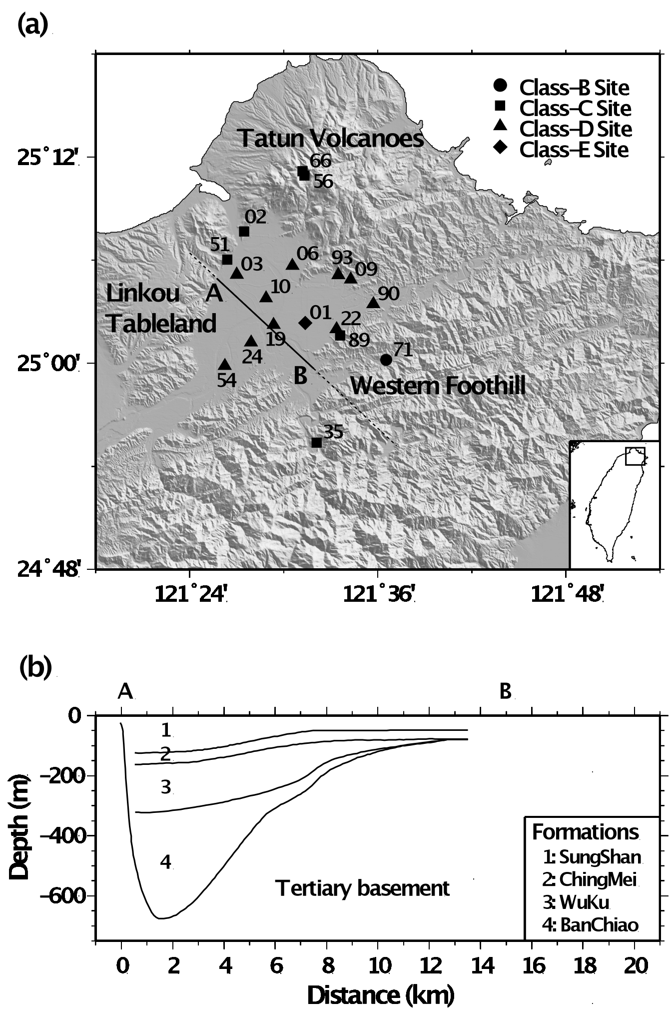

Figure 1. (a) A map to show the Taipei Basin and surrounding geological provinces. The station sites in use are displayed in circles, squares, triangles, and diamonds for Class-B, C, D, and E sites, respectively; and (b) Subsurficial geological structures in the Taipei Basin (modified from Wang et al., 2004).

GEOLOGICAL SETTING

The Taipei Basin (see Figure 1a) is specified with sedimentary layers (CGS 1999; Wang et al. 2004; Wang-Lee and Lin 1987). In the basin, Quaternary sediments lie on a Tertiary basement. The Quaternary sediments are composed of three formations, i.e., the Sungshan, Chingmei, and Hsinchuang formations from top to bottom. Teng et al. (1994) divided the Hsinchuang formation into two, i.e., the Wuku and Banchiao formations. Figure 1b shows the subsurface geological structures along Line AB depicted in the SE-NW direction as shown in Figure 1a. The topmost part of the Sungshan formation is a soft layer, which composes of unconsolidated sand, silt and clay with a thickness varying from 50 m in the southeast to 120 m in northwest. The lower part of the formation is dominated by silt. The Chingmei formation is full of gravels. The Hsinchuang formation is composed of sand and silt. From shallow reflection experiments and the borehole drilling results, Wang et al. (2004) concluded that the three layers of the Sungshan formation are specified with low V_s, i.e., 170, 230, and 340 m/s, respectively. The values of V_s in the Chingmei, Wuku, and Banchiao formations are, respectively, 450, 600, and, 880 m/s. The uncertainties of V_s are lower for the former formation than the latter two. The value of V_s of the Tertiary basement is about 1500 m/s.

METHOD

We applied the method developed by Boore and Joyner (1997) to evaluate the frequency-dependent site amplifications. At a particular frequency, the amplification is the squared root of the ratio of the seismic impedance (velocity times density) averaged over a depth range corresponding to a quarter wavelength to that at the depth of the source of seismic waves. For this method, the incident-plane waves through attenuation corrections are taken into account. They defined the amplification to be the ratio of the Fourier amplitude spectrum of the surface motion produced for un-attenuated incident plane waves to that recorded at the surface of a uniform half-space by the same incident waves. The amplification decreases with wavelength, therefore, approaches unity for very long-period waves. They denoted S_{tt}, $\beta_z=z/S_{tt}$, and ρ_z, respectively, to be the average S-wave travel time, the average velocity, and the average density. The average density is defined to be $S_{tt}^{-1}\cdot\Sigma(z_i\rho_i/\beta_i)$, where z_i, ρ_i, and β_i are the thickness, density, and S-wave velocity in the i-th layer in consideration. From the three quantities, they evaluate the frequency, i.e., $f=1/(4\cdot S_{tt})$, and the site amplification, i.e.,

$$A(f)=(\rho_s\beta_s/\rho_z\beta_z)^{1/2}, \tag{1}$$

where the subscript "s" represents the source area, associated with the layer thickness of z from which the seismic waves are incident to the sediments. The above-mentioned five quantities are all defined from the ground surface to depth z.

BOREHOLE DATA

There are 11 boreholes inside the Taipei Basin. For the purpose of comparison, 7 boreholes located outside but near the Taipei Basin are also taken into account. The localities of the 18 boreholes are shown in Figure 1a. The core samples of the 18 sites show that geological materials below them belong to the Sungshan formation, which is a soft layer and composes of unconsolidated sand, silt and clay. The depths of the 18 boreholes range from 31 to 56 m. The majority of the boreholes have a depth of 30 m. The depths of 2 boreholes, respectively, at a Class-D site and a Class-E one are greater than 40 m.

At each borehole, V_s is measured every 0.5 m. The depth profiles of V_s at four borehole sites: 71 (Class-B), 02 (Class-C), 09 (Class-D), and 01 (Class-E) are shown in Figure 2a with a solid line. The total number of samples of V_s loggings is 1126 and the measured values are in the range 93–1235 m/s. The ranges of measured shear velocities at the 18 boreholes are shown in Figure 2b, where all sites are projected to Line AB in Figure 1. Except for few sites, the velocity range is smaller inside than outside the Taipei Basin. Inside the basin, except for sites 09 and 22, the maximum velocity is less than 500 m/s. The maximum velocity is larger to the east than to the west of the basin. The US's criteria to classify sites (cf. Lee et al. 2001) are based on V_{30}: the Class-A site with V_{30}>1500 m/sec, the Class-B one with V_{30}=760–1500 m/s, the Class-C one with V_{30}=360–760 m/s, the Class-D one with V_{30}=180–360 m/s, and the Class-E one with V_{30}<180 m/s, where V_{30} is the averaged shear-wave velocity in the topmost 30 m layer. Based on the criteria, Lee et al. (2001) classified the 708 free-field strong-motion station sites in Taiwan from surficial geology. However, from the well-logging data, Huang et al. (2007) found that it is necessary to re-classify the station sites in Taiwan. For the Taipei Basin, the classes of 13 station sites must be revised. Well-logging data show that among the 18 sites in Figure 1, there is a Class-B site (denoted by a circle), 6 Class-C sites (denoted by squares), 10 Class-D sites (shown by triangles), and a Class-E site (depicted by a diamond). The Class-B and C stations sites are located at the mountains outside the Taipei Basin, while the Class-D and E ones inside the basin.

Unlike V_s, ρ was not measured regularly every 0.5 m and only done at one point in a certain geological layer. The total number of logging samples of ρ is 308 and the measured values are in the range 1.3–2.3 gm/cc. At some well-logging points, where the V_s was measured, yet lack of ρ, the value of ρ measured at a nearby one, which belongs to the same geological layer as the former, is assigned. A complete well-logging profile including the two parameters can, thus, be constructed at each borehole site. Included also in Figure 2a are the values of ρ (denoted by a solid circle) at four borehole sites: 71 (Class-B), 02 (Class-C), 09 (Class-D), and 01 (Class-E).

An important site factor in predicting ground motions and in constructing the building codes (Boore and Joyner 1997) is the averaged shear velocity from the ground surface to 30-m depth, i.e., $V_{30}=30/S_{tt}(30)$, which is plotted in Figure 2b with an open square. Except for few sites, V_{30} is smaller inside than outside the basin. Unlike the maximum velocity, V_{30} is relatively uniform inside the basin. At sites 09 and 22, V_{30} is small, even though the maximum velocities are large. This means that lower V_s dominates the core samples at the two sites.

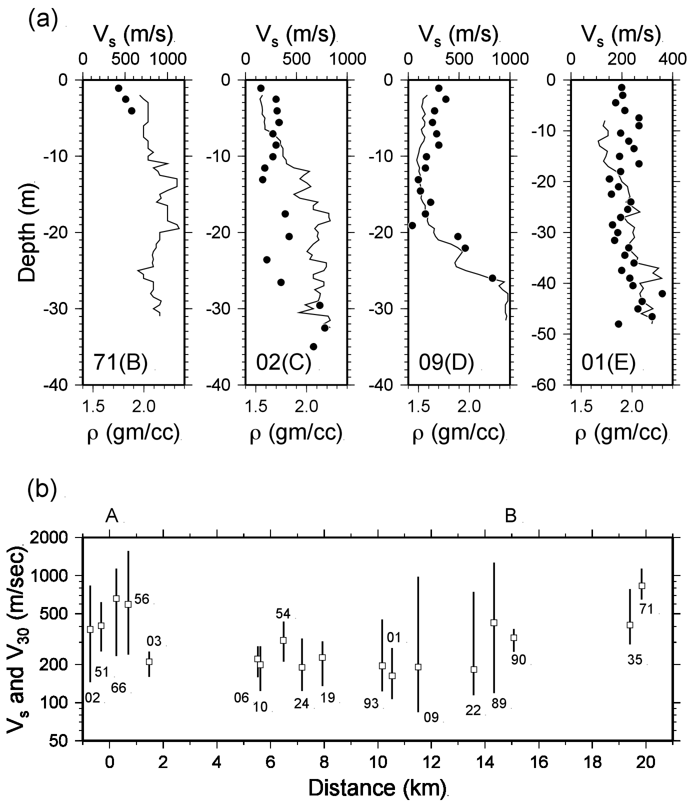

Figure 2. (a) Four examples of well-loggings of *S*-wave velocity (lines) and density (circles) varied with depth; and (b) the measured velocity range (in a vertical line segment) and V_{30} (in an open square) at each borehole site, whose station code is given in and locality is projected on Line AB shown in Figure 1a. (from Huang et al., 2009)

EVALUATIONS OF SITES AMPLIFICATIONS

There are two steps for calculating the frequency-dependent site amplifications of shallow sediments relative to the Tertiary basement in the Taipei Basin. On the first step, we evaluate the amplifications as a function of frequency at each site on the basis of Eq. (1). For this purpose, the values of β_s and ρ_s of the basement are needed. From the velocity model inferred by Wang et al. (2004), we take the average shear velocity, i.e., 1500 m/s, of the Tertiary basement to be β_s. There is no detailed density model right below the Taipei Basin due to limited gravity data. From the gravity survey in the Tatun Volcano Group (TVG), just to the north of the Taipei Basin, Tzou and Yu (1987) inferred that from top to bottom there are three layers with different densities: 2.40 gm/cc in the range 0 to 400 m, 2.45 gm/cc in the range 400 to 1600 m, and 2.55 gm/cc below 1600 m. In the basin the thickness of sediments ranges from 100 m to 700 m; while outside the basin the sediments become thin. The 3-D velocity tomography (Ma et al. 1996) shows that the deeper structures below TVG and the basin are similar. Hence, we can take the density (=2.45 gm/cc) of the second layer to be ρ_s. From the well-logging V_s and ρ, we calculate the values of A(f) and f. The plots of A(f) versus f are displayed in Figure 3 with different symbols: circles, squares, triangles, and diamonds, respectively, for the Class-B, C, D, and E sites. The frequency ranges are different for the four classes of sites. The values of $V_{30}=30/S_{tt}(30)$ (in m/s) controls the lower bound frequency, f_{30}, which is associated with a 30-m layer. As displayed in Figure 2b, V_{30} is 832.5 m/s and 162.0 m/s, respectively, for the Class-B and E sites, and in the range of 375.7–661.1 m/s for Class-C and 182.4–324.6 m/s for Class-D. Therefore, the values of f_{30} are: 6.9 Hz for the Class-B site, 3.1–5.5 Hz for Class-C, 1.5–2.7 Hz for Class-D, and 1.3 Hz for Class-E. As taking the deepest borehole at each class taken into account, the value of f_{low} can reach 6.9 Hz for the Class-B site, 3.1 Hz for Class-C, 1.1 Hz for Class-D, and Class-E. This can be seen in Figure 3 that for the Class-C sites, except for few boreholes deeper than 30 m, there are no data points for f<3 Hz. Obviously, the plots can be divided into four groups, which are associated, respectively, with the Class-B, C, D, and E sites from bottom to top. Of course, the plots of the unique Class-E site are inside the Class-D group.

On the second step, the average amplifications are calculated from those of individual sites at the same borehole depth. Of course, for a certain depth the frequencies at different sites vary in a small range due to unequal velocity profiles. The average frequency is taken to be the frequency related to such a depth. The values of A(f) at several frequencies are shown in Table 1. Since there is only one site for Class-B and Class-E, therefore, it is not necessary to take the average for them. When f<2.3 Hz, the numbers of well-logging data for the Class-D sites are also only one (see Table 1). The data points of average amplification versus average frequency are displayed in Figure 3 as solid symbols, i.e., circles, squares, triangles, and diamonds, respectively, for the Class-B, C, D, and E sites. Included also in Figure 3 are the error bars of both A(f) and f for the Class-C and D sites. At the Class-B site, A(f) first slightly decreases and then increases with increasing f from 7 to 50 Hz. The values of A(f) vary in a small range of from 1.5 to 1.6. At the Class-C sites, average A(f) first increases with f, and then almost becomes a constant of about 3.0 when average f>12 Hz. However, the value of A(f) at f=3.5 Hz is larger than that at f=4 Hz. At the D sites, average A(f) first increases with f and suddenly drops to a smaller value at f=2 Hz, then increases with f again and finally almost becomes a constant of about 3.6 when f>10 Hz. When f<10 Hz, the increasing rate is much larger for the Class-C sites than for the Class-D ones. When f>10 Hz the data points for the Class-C and D sites are somewhat below the individual trend. This might be due to lower reliability of measured values at shallow depths, because it is not easy to exactly measure the values of V_s and ρ in fragmented soil layers from seismic reflections. At the Class-E site, A(f) first increases and then decreases with increasing f. The values of A(f) vary from 3.0 to 3.8, with a peak at f=2 Hz. The amplifications of the Class-E site approximately reach a value of 3.6 when f>7 Hz.

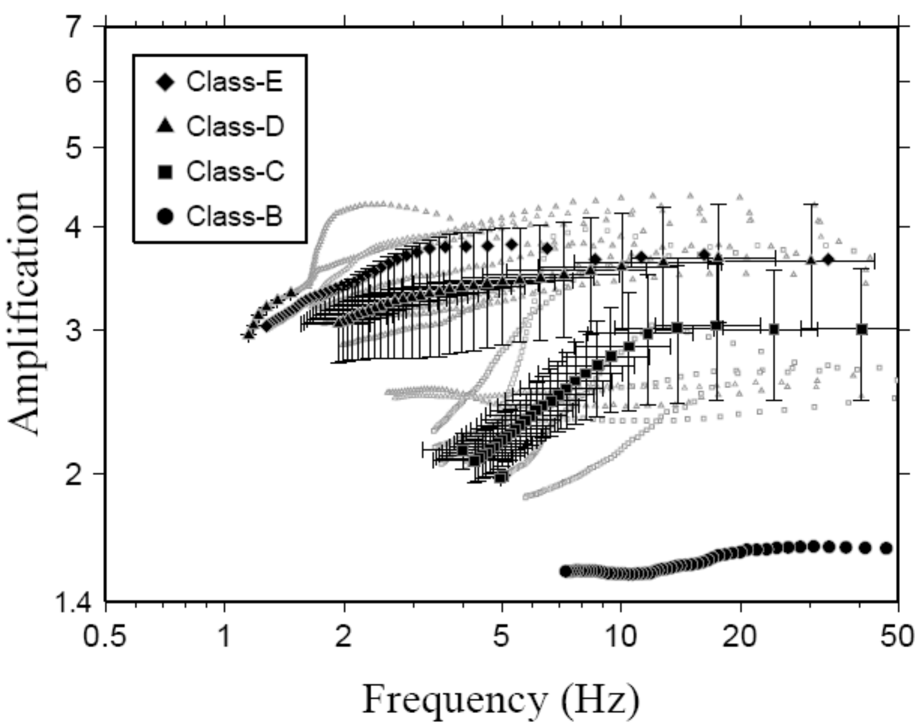

Figure 3. The plots of A(f) versus f: circles, squares, triangles, and diamonds for Class-B, C, D, and E sites, respectively. (A)The average values, with error bars, from various boreholes at the same depth are displayed by solid symbols. (modified from Huang et al., 2009)

SUMMARY

Results show that the site amplifications at all sites in study are larger than 1 and a function of frequency. At the Class-B site, A(f) first slightly decreases and then increases with increasing f, varying from 1.5 to 1.6. At the Class-C sites, average A(f) first increases with f, and then almost becomes a constant of about 3.0 when average f>12 Hz. At the D sites, average A(f) first increases with f and suddenly drops to a smaller value at f=2 Hz, then increases with f again and finally almost becomes a constant of about 3.6 when f>10 Hz. At the Class-E site, A(f) first increases and then decreases with increasing f, varying from 3.0 to 3.8, with a peak at f=2 Hz. Compared with the Haskell method, the quarter-wavelength approximation is almost an average and a good representation of the overall amplifications. For the unique site, the amplification function cannot represent the averaged site response of Class-B and E site. However, it is noted that the site amplifications evaluated in this study can apply only to frequencies greater than about 1.1 Hz for Class-C sites and 3.1 Hz for Class-D ones.

Table 1. The values of *A*(*f*) at several frequencies for four classes of sites. The number of boreholes at the same depth used in estimating the values *A*(*f*) is given in the parentheses. (from Huang et al., 2009)

f (Hz)	Class-B	Class-C	Class-D	Class-E
1.1			2.8 (1)	3.0 (1)
1.3			3.2 (1)	3.0 (1)
1.5			3.3 (1)	3.2 (1)
2.0			3.1 (1)	3.4 (1)
2.3			3.2 (10)	3.5 (1)
2.7			3.2 (10)	3.6 (1)
3.1		2.0 (1)	3.3 (10)	3.7 (1)
4.0		2.1 (3)	3.4 (10)	3.8 (1)
5.0		2.2 (6)	3.4 (10)	3.8 (1)
6.0		2.4 (6)	3.5 (10)	3.8 (1)
6.9	1.5 (1)	2.6 (6)	3.5 (10)	3.7 (1)
11.0	1.5 (1)	2.9 (6)	3.6 (10)	3.7 (1)
25.0	1.6 (1)	3.0 (6)	3.6 (10)	3.6 (1)
30.0	1.6 (1)	3.0 (6)	3.6 (10)	3.6 (1)

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