Seismic microzonation of the greater Bangkok area using microtremor observations

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SUMMARY

Bangkok, the capital city of Thailand, is located at a remote distance from seismic sources. However, it has a substantial risk from these distant earthquakes due to the ability of the underlying soft clay to amplify ground motions. It is therefore imperative to conduct a detailed seismic hazard assessment of the area. Seismic microzonation of big cities, like Bangkok, provides a basis for site-specific hazard analysis, which can assist in systematic earthquake mitigation programs. In this study, a seismic microzonation map for the greater Bangkok area is constructed using microtremor observations. Microtremor observations were carried out at more than 150 sites in the greater Bangkok area. The predominant periods of the ground were determined from the horizontal-to-vertical (H/V) spectral ratio technique. A microzonation map was then developed for the greater Bangkok area based on the observations. Moreover, the transfer functions were calculated for the soil profile at eight sites, using the computer program SHAKE91, to validate the results from the microtremor analysis. The areas near the Gulf of Thailand, underlaid by a thick soft clay layer, were found to have long natural periods ranging from 0.8 s to 1.2 s. However, the areas outside the lower central plain have shorter predominant periods of less than 0.4 s. The study shows that there is a great possibility of long-period ground vibration in Bangkok, especially in the areas near the Gulf of Thailand. This may have severe effects on long-period structures, such as high-rise buildings and long-span bridges. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: microzonation; Bangkok; microtremors; predominant period; H/V spectral ratio

1. INTRODUCTION

Local ground conditions substantially affect the characteristics of incoming seismic waves during earthquakes. Flat areas along the coast and rivers generally consist of thick layers of soft clay and sand. The soft deposits amplify certain frequencies of ground motion thereby increasing earthquake damage. A well-known example is Mexico City in the 1985 Michoacan

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earthquake. Mexico City is built on the former bed of a drained lake over a soft soil deposition of lacustrine origin. The fault rupture in this earthquake was around 350 km away from the city; however, Mexico City sustained catastrophic damage due to the strong amplification of the ground motion by soft soil deposits [1, 2]. The devastation caused in Mexico City due to the strong amplification of the ground motion by superficial deposits reflects the potential hazard from distant earthquakes in modern cities built over soft deposits.

Although Bangkok, the capital city of Thailand, is located in a low seismic hazard area, there is a potential hazard from distant earthquakes due to the ability of underlying soft clay to amplify ground motions [3]. The variation in the ground motion, according to the geological site conditions, makes it necessary for big cities like Bangkok to conduct seismic microzonation. Seismic microzonation is defined as the process of subdividing an area into zones with respect to geological characteristics of the sites, so that seismic hazards at different locations within a city can correctly be identified [4]. Microzonation provides the basis for a site-specific risk analysis, which can assist in the mitigation of earthquake damage. No studies have been carried out for the microzonation of Bangkok to date.

This study is focused on the microzonation of the greater Bangkok area using microtremor observations at different sites. The microtremor method measures ambient vibrations in the order of microns present on the ground surface. The main sources of these vibrations are traffic, and industrial and human activities [5]. Observation of these microtremors can be used to determine the predominant period of vibration of a site [6–8]. Nakamura [6] proposed the H/V spectral ratio method, in which the predominant period of the ground vibration is determined by the ratio of horizontal and vertical Fourier spectra of microtremors recorded at a site. A number of experimental investigations have validated the reliability of the H/V method in determining the predominant period of the ground [9–11].

The conventional means for determining the soil profile is the borehole method. However, this method is costly and time consuming, and hence it is generally not suitable for micro-zonation. Methods based on the analysis of strong-motion records are more straightforward for determining site effects. However, the availability of ground motion records is limited to a very few countries. The strong-motion records for Thailand are very limited, and hence are not adequate for estimating the site effects. In this context, microtremor observation becomes the most appealing approach for site-effect studies. Another non-intrusive method for determining the shear wave velocity profile is the spectral-analysis-of-surface-wave (SASW) method which is based on evaluating Rayleigh-wave dispersion at a site, from which the V_s profile is evaluated [12].

The area of study (Figure 1) is located within latitudes 13°30′ N and 14°30′ N and longitudes 99°45′ E and 101°30′ E, including the Bangkok metropolitan area and the areas in the vicinity. Microtremor measurements were performed at more than 150 sites in the greater Bangkok area and the H/V spectrum ratio technique was applied to estimate the predominant periods of the ground vibration at all the sites. A microzonation map for the city was then developed based on the results of the H/V analysis.

2. SEISMICITY OF BANGKOK

Thailand lies in the east of the Andaman–Sumatra belt. Nutalaya *et al.* [13] identified twelve seismic source zones in this region (Figure 2) after a comprehensive study on the

Figure 1. Area of study.

seismo-tectonic features of the Burma–Thailand–Indochina region. The major active faults are far from Bangkok, between 400 km and 1000 km away. Some active faults are found in the western parts of Thailand at around 120 km to 300 km from Bangkok; however, their seismic activities are low in terms of recurrence interval and expected maximum magnitude. The study indicates that there are at least seven active faults in northern Thailand (Zone G) and five active faults in western Thailand (the lower portion of Zone F). It was estimated from their expected rupture dimensions that maximum earthquakes of magnitude (M_W) 6.8 to 7.2 and 7.3 to 7.5 could be generated in northern and western Thailand, respectively.

More than 20 earthquake ground shakings have been felt in Bangkok in the last 200 years. Although some of the ground shakings were strong enough to cause alarm among the people, there has been either no damage or very trivial damage to the structures in Bangkok due to the ground motions. Table I lists the significant earthquake events that have been felt in Bangkok in the past 100 years. The epicenters of the earthquakes are shown in Figure 2 with gray circles.

Warnitchai and Lisantono [14] conducted a probabilistic seismic hazard analysis in Thailand and proposed a seismic zonation map for Thailand. According to this study, Bangkok lies in Zone I ($0.025\,g < \mathrm{PGA}_0 < 0.075\,g$), where PGA_0 is the peak ground acceleration having a 10% probability of being exceeded in a 50-year period; however, this study does not consider the site effect. Another study carried out by Warnitchai et al. [3] identified that the soil profile underlying Bangkok has the ability to amplify earthquake ground motions by about 3 to 6 times for low-intensity input motions (peak rock acceleration smaller than $0.02\,g$) and about 3 to 4 times for relatively stronger input motions (peak rock acceleration larger than $0.02\,g$). They identified three factors as the main causes of the hazard. First, several regional seismic sources that may contribute significantly to the seismic hazard of Bangkok are capable of generating large earthquakes. Second, the attenuation rate of ground motions in this region appears to be rather low; and third, the surficial deposits in Bangkok have the ability to amplify earthquake ground motions by about 3 to 4 times (Figure 3).
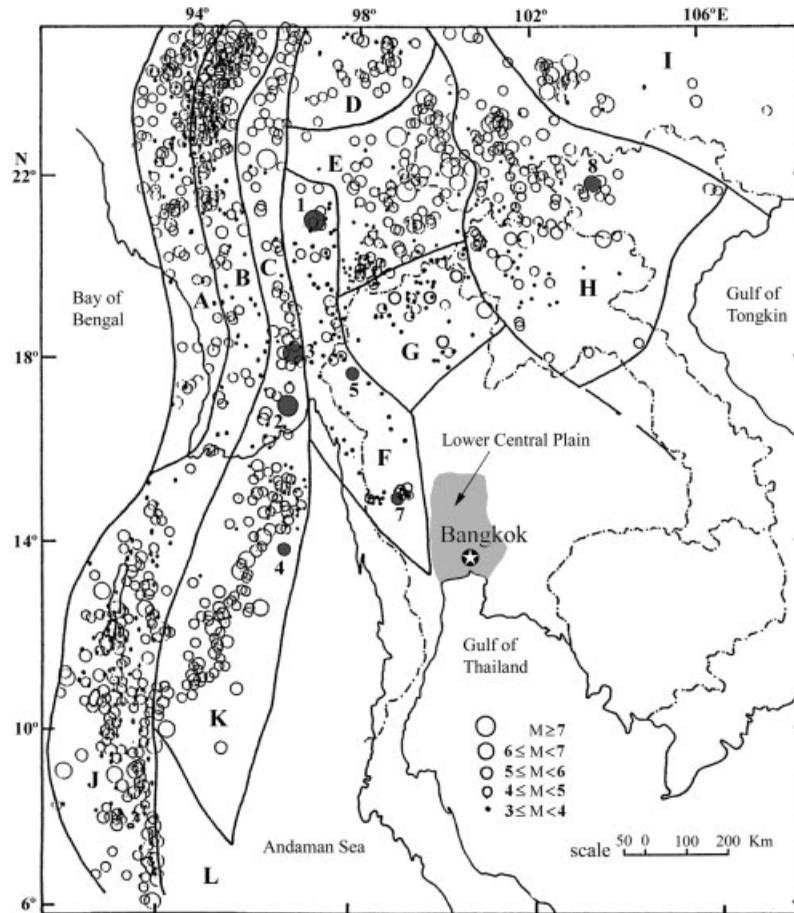
Figure 2. Seismic source zone map and the epicenters of earthquakes that
occurred from 1910 to 2000 [3, 13].

The seismic design regulation in Thailand [15] prescribes the design requirements similar to 1985 UBC Zone 2 for ten provinces, which do not include Bangkok. Hence, most of the buildings and structures in Bangkok have been designed and constructed without any consideration of seismic loading.

GEOLOGY OF BANGKOK

Bangkok is situated on a large plain underlain by the thick alluvial and deltaic sediments of the Chaophraya basin. This plain, generally known as the Lower Central Plain, is about 13 800 km^2 in area [16]. The plain was under a shallow sea 5000 to 3000 years ago, and the regression of the sea took place around 2700 years ago, leaving the soft clay deposits, which now form the lower central plain (Figure 4). This plain consists of thick clay known as Bangkok clay on its top layer, and its thickness is about 15 m to 20 m in the Bangkok metropolitan area

Table I. Summary of the earthquake events felt in Bangkok [13].

No.	Earthquake location	Date	Epicentral coordinates	Focal depth (km)	Magnitude	Epicentral distance from Bangkok (km)
1	Mandalay[a]	23 May 1912	21° N 97° E	35	8.0 (M_s)	870
2	Pegu[a]	5 May 1930	17.3° N 96.5° E	35	7.2 (M_s)	580
3	Pyu[a]	4 December 1930	18.2° N 96.4° E	35	7.2 (M_s)	660
4	Andaman[a]	14 February 1967	13.7° N 96.5° E	30	5.6 (m_b)	440
5	Tak[a]	17 February 1975	17.6° N 97.9° E	6	5.6 (m_b)	500
6	North Sumatra Island	04 April 1983	5.7° N 94.7° E	85	6.6 (M_s)	1100
7	Kanchanaburi[a]	22 April 1983	14.92° N 99.05° E	32	5.9 (M_s)	210
8	Chinese–Vietnam Border[a]	24 June 1983	21.7° N 103.3° E	18	6.1 (m_b)	910
9	North Sumatra Island[b]	22 January 2003	4.5° N 97.5° E	33	5.8 (m_b)	1200

[a]Epicenters of the earthquake events are marked in Figure 2 with shaded circles and respective serial numbers.
[b]National Earthquake Information Center (NEIC), US Geological Survey.
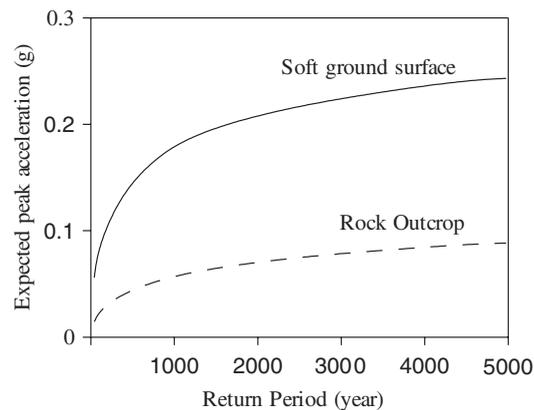
Figure 3. Seismic hazard curve for Bangkok [3].

(Figure 4). The soft clay has very low shear strength, and is highly compressible, as it has never been subjected to mechanical consolidation.

The uppermost weathered crust exists to a depth of 1 to 5 m. The thickness of soft clay increases towards the sea and decreases rapidly in the northerly direction from Bangkok. The first stiff clay layer exists below the soft clay layer. It is generally 5 to 7 m thick in central Bangkok and its thickness decreases towards the north and west of central Bangkok. The first sand layer is found beneath the stiff clay layer up to a depth of around 50 m. At greater depths, alternate layers of stiff clay and sand layers are found. The bedrock is found at the large depths varying from 500 m to 2000 m beneath the unconsolidated sediments and its structure is poorly known [16].
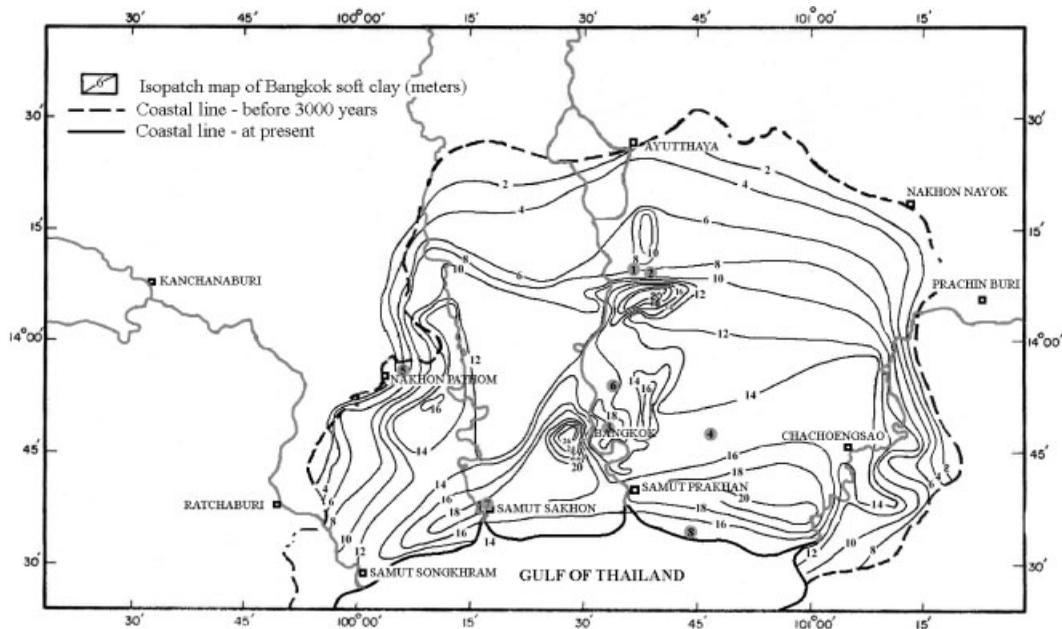
* Gray circles are the location of eight sites mentioned in Figure 5.

Figure 4. Isopatch map showing the thickness of soft clay in Bangkok [16].

The *in situ* S-wave velocity (V_s) measurement performed in Bangkok shows notably low V_s in soft Bangkok clay (about 60 to 100 m/s) [17–19]. Shear wave velocity for the first stiff clay layer was found to be in the range 150–200 m/s. V_s was found to increase to about 250 m/s in the first sand layer, and to continue to increase, although at a slower rate, in the deeper strata [17–19]. The low V_s for Bangkok soft clay and the first stiff clay layer is comparable to that of Mexico City clay [3]. Moreover, the drastic increase of the V_s in the first sand layer can aggravate the amplification of ground motion.

MICROTREMOR MEASUREMENT AND DATA ANALYSIS

Instrument set-up

Microtremor observations were performed using portable microtremor equipment. GEODAS (Geophysical Data Acquisition System) made by Butan Service Co. (Japan) was used for the data acquisition. The sampling frequency for all the measurements was set at 100 Hz. The low-pass filter of 50 Hz was set in the data acquisition unit. The velocity sensor used can measure three components of vibration: two horizontal and one vertical. The natural period of the sensor is 2 s. The available frequency response range for the sensor is 0.5–20 Hz. A global positioning system (GPS) was used for recording the coordinates of observation sites.

Data acquisition and processing

Microtremor observations were carried out at more than 150 sites in the greater Bangkok area. The measurements were carried out along the highways that run in the radial directions from central Bangkok, at a distance interval of approximately 10 km. The observations were conducted along the small streets at least 100 m away from the busy highways. However, inside the Bangkok metropolitan area most of the measurements were carried out in open public spaces, such as parks, schools, universities, temples and government offices.

At each site, data was recorded for 327.68 seconds (i.e. 32768 data points at the sampling rate of 100 Hz). The recorded time series data were divided into 16 segments each of 20.48 s duration. For each site, ten segments of the data were chosen from 16 segments, omitting the segments that are influenced by very-near noise sources. These ten segments were used for the calculations. The Fourier spectra were calculated for the selected ten segments using the Fast Fourier Transform (FFT) algorithm and the Fourier spectra were smoothed using a Parzen window of bandwidth 0.4 Hz. The Fourier amplitude ratio of the two horizontal Fourier spectra and one vertical Fourier spectrum were obtained using Equation (1):

$$r(f) = \frac{\sqrt{F_{NS}(f) \times F_{EW}(f)}}{F_{UD}(f)} \tag{1}$$

where $r(f)$ is the horizontal to vertical (H/V) spectrum ratio, and F_{NS}, F_{EW} and F_{UD} are the Fourier amplitude spectra in the NS, EW and UD directions, respectively.

After obtaining the H/V spectra for the ten segments, the average of the spectra were obtained as the H/V spectrum for a particular site. The peak period of the H/V spectrum plot shows the predominant period of the site.

The H/V spectra were obtained for all the observation sites and the predominant periods of ground motion for all the sites were identified. Observation points were then overlaid on a digital map of the greater Bangkok area and the inverse distance weighting (IDW) method [20] was used for spatial interpolation from the data measured at discrete locations.

SOIL AND SHEAR WAVE VELOCITY PROFILES OF BANGKOK SUBSOIL

In the context of Bangkok, the number of sites with S-wave velocity (V_s) profile is very limited. In this study, soil profiles at eight different sites in the greater Bangkok area were analyzed (Figure 5). The location of these eight sites are shown in Figure 4 as gray circles with numbers corresponding to the sites as shown in Figure 5. Among the eight sites chosen, detailed V_s profiles were available at four sites: Asian Institute of Technology (up to 60 m depth), Thamasart University Rangsit (up to 50 m depth), Chulalongkorn University (up to 60 m depth) and Ladkrabang (up to 15 m depth) from *in situ* downhole measurement [17–19]. Based on these observations, Ashford *et al.* [18] proposed a generalized V_s profile for Bangkok subsoil. However, owing to lack of observation data after 60 m, Ashford *et al.* [18] estimated the V_s profile down to the depth of 80 m based on available data: SPT N-values and shear strength (S_u). Moreover, after the depth of 80 m there were no data available for them to make a reasonable estimate. The generalized S-wave velocity profile proposed by Ashford *et al.* [18] assumes that a rock-like material exists below the depth of 80 m with an S-wave velocity of 900 m/s. However, the number of deep borings carried out around Bangkok reveals
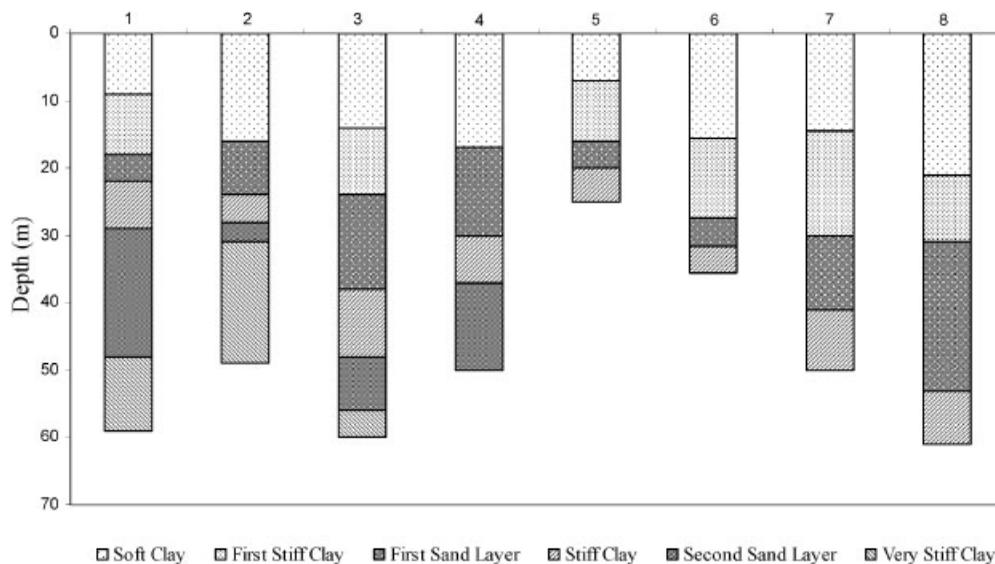
Figure 5. Soil profile at eight sites in the greater Bangkok area. (1: Asian Institute of Technology; 2: Thamasart University Rangsit; 3: Chulalongkorn University; 4: Ladkrabang; 5: Nakhon Pathom; 6: Chatuchak; 7: Samut Sakhon; 8: Ban Tamru.)

that the bedrock lies very deep below the ground surface, ranging from 500 m to 2000 m at some sites [16]. This therefore suggests that it may not be reasonable to assume bedrock of S-wave velocity 900 m/s at the depth of 80 m. Hence, an effort was made to roughly estimate the S-wave velocity at larger depths from empirical formulae using available data. The only data available for larger depths was the compressive strength for some sites [21]. At the Samut Sakhon site in the south near the Gulf of Thailand, the compressive strength of soil was available to a depth of 600 m. At this site it can be observed that there is no drastic increase in the compressive strength of the soil even at larger depths. Although there is no direct relationship between the compressive strength of soil and the S-wave velocity, empirical formulae (Equations (2)–(4)) were used to roughly estimate the S-wave velocity at the lower layers from the compressive strength data available at the site [21].

The unconfined compressive strength (Q_u) and shear strength (S_u) of soil can be related by the relationship:

$$S_u = Q_u/2 \qquad (2)$$

The empirical formula developed by Seed and Idriss [22] can be used to estimate the small shear strain modulus (G_{max}) from the undrained shear strength (S_u):

$$G_{max} = 2200S_u \qquad (3)$$

where G_{max} and S_u are in t/m^2.

Then, the S-wave velocity for the soil layer can be obtained by

$$V_s = \sqrt{G_{\mathrm{max}}/\rho} \tag{4}$$

where ρ is the mass density of soil.

The estimated S-wave velocity profile at this site shows that there is no sudden increase in the S-wave velocity even at larger depths. The S-wave velocity is of the order of 400 m/s at the depth of 80 m and it increases to approximately 500–600 m/s at depths of 80–120 m. There is also no marked increase in the S-wave velocity at greater depths.

Hence, in this study V_s profiles for these four sites were taken up to the depth where shear wave velocity profiles were available from *in situ* downhole measurement [17–19]. After these depths, the V_s profile is estimated from SPT-N values and shear strength (S_u) using the set of equations proposed for the Bangkok subsoil by Ashford *et al.* [17]; after the depth of 120 m, V_s was taken as 550 m/s. The S-wave velocity profiles for these four sites are shown in Figure 6.

Soil profile data were also available for another four sites (Nakhon Pathom, Chatuchak, Samut Sakhon, and Ban Tamru), where microtremor observations were also conducted. These sites were also used for the comparison between the results from the microtremor observations and the transfer functions obtained by SHAKE91. For these four sites, the S-wave velocity profiles were estimated from SPT N-values and shear strength (S_u) using the set of equations proposed for the Bangkok subsoil by Ashford *et al.* [17]. The estimated S-wave velocity profiles for these four sites are shown in Figure 6.

Approximate calculation of site period

If a soil deposit is assumed as one layer, with constant density and shear wave velocity, over a stiff base, the characteristic site period can be calculated from

$$T = \frac{4H}{V_s} \tag{5}$$

where T is the site period, H is the depth of bedrock and V_s is the shear wave velocity of the soil deposit. However, in reality, the soil deposit seldom consists of a single layer; rather it consists of a number of strata. For stratified subsoil deposited over a firm base, the predominant period can be obtained using Equation (6) [23–25]:

$$T = 4 \sum \frac{H_i}{V_{si}} \tag{6}$$

where H_i is the thickness of each constituent layer and V_{si} is the shear wave velocity within that layer.

From Figure 6 we can see that there is a high impedance ratio between the first stiff clay layer and the first sand layer. Hence, considering the first sand layer as a firm base layer, Equation (7) can be used to estimate the characteristic site period for the soft soil deposit for the eight sites:

$$T = 4 \sum \left(\frac{H_1}{V_1} + \frac{H_2}{V_2} \right) \tag{7}$$
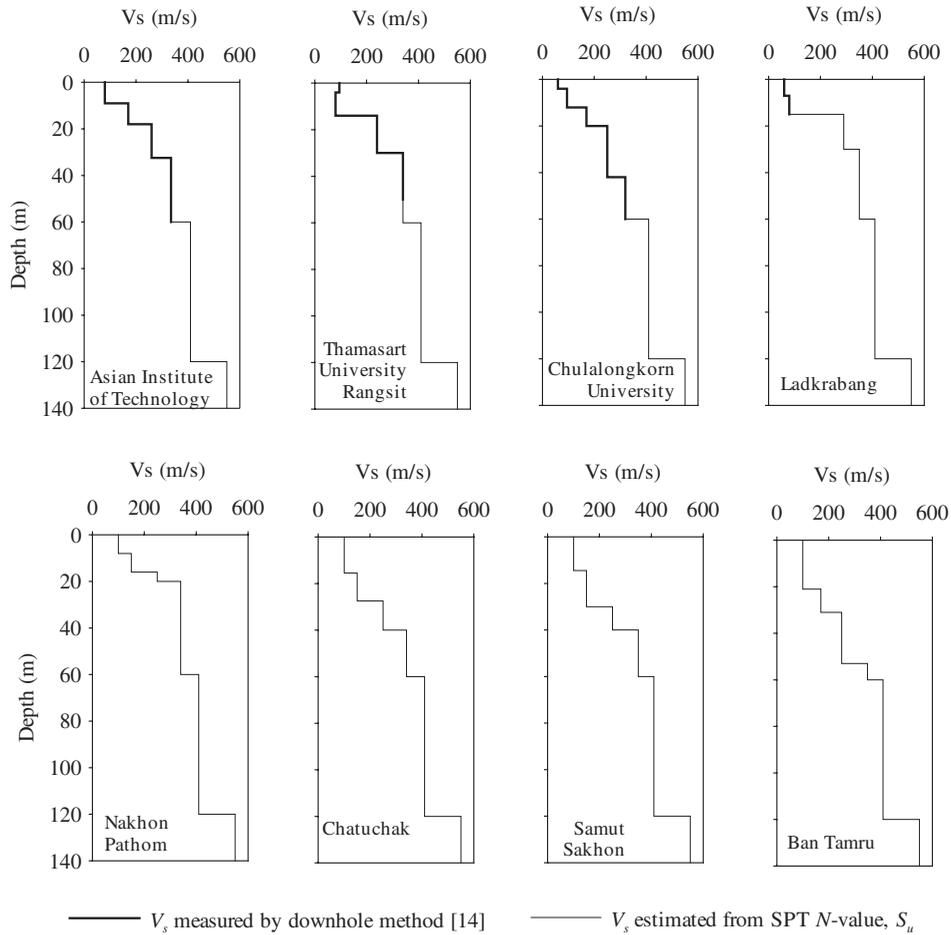
Figure 6. S-wave velocity profile for eight sites in the greater Bangkok area.

where H_1 and V_1 are the thickness and shear wave velocity for the soft clay layer and H_2 and V_2 are the thickness and shear wave velocity for first stiff clay layer.

The characteristic periods for the soft soil deposits for the eight sites computed using Equation (7) are compared with the predominant periods obtained from microtremor observations in Figure 7. It can be observed from the figure that there is a good correlation between the predominant periods obtained from microtremor observations and the periods obtained from Equation (7).

Transfer function of Bangkok sites using SHAKE91

The transfer functions were calculated using the computer program SHAKE91, for the eight sites where microtremor data were also available (Figure 8). Here, the transfer function is defined as the ratio of surface Fourier spectrum to the rock outcrop Fourier spectrum.
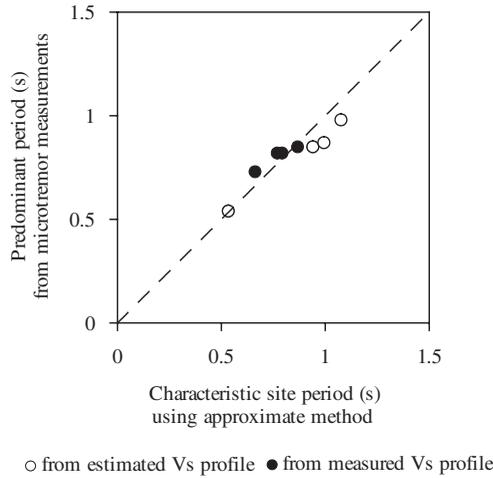
Figure 7. Predominant period from the microtremor observation and approximate method.
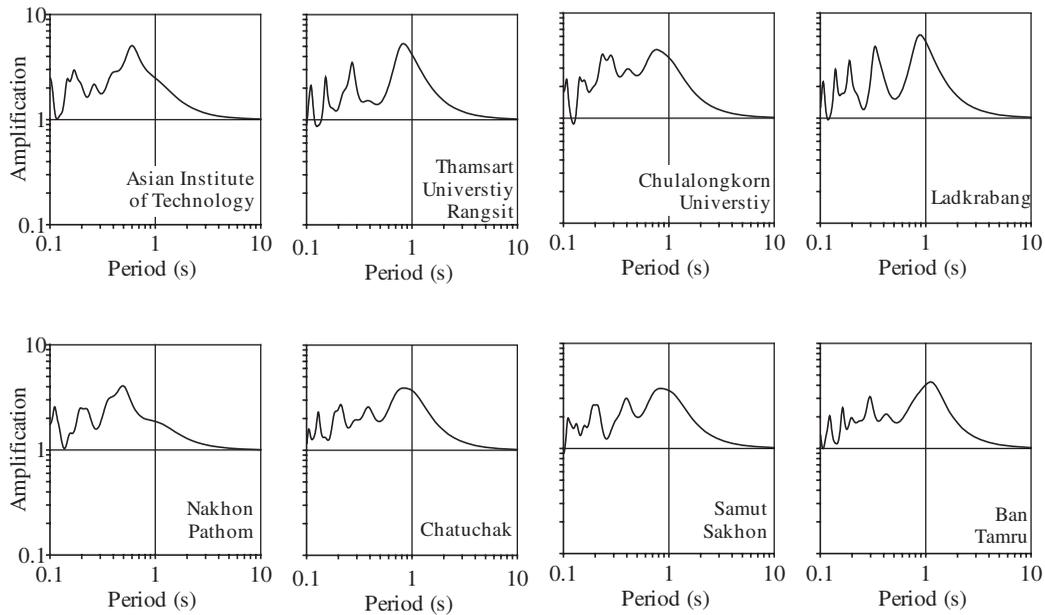
Figure 8. Transfer function calculated for eight sites in the greater Bangkok area using SHAKE91.

As stated earlier, the microtremor observations measure the vibration in the range of microns. At such low strains, soil basically behaves as a linear material having a constant damping ratio and a shear modulus. The transfer functions were computed assuming the damping ratio as 2% of critical.

The H/V spectral ratios from microtremor observations for the eight sites are shown in Figure 9. The predominant periods obtained from the transfer functions of the subsoil at the
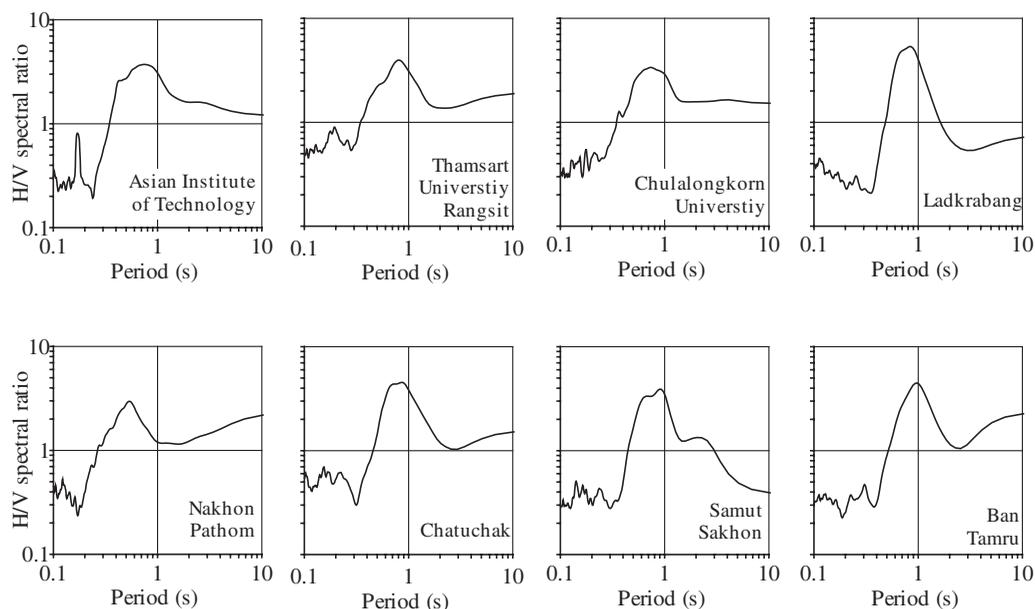
Figure 9. *H/V* spectral ratio for the eight sites from microtremor measurements.

eight sites are analogues to the predominant periods obtained from the microtremor observation at the respective sites (Figure 10).

RESULTS OF THE MICROTREMOR MEASUREMENTS

The microtremor measurements show that the sites located near the Gulf of Thailand have a considerably long predominant period, around 0.8 s to 1.2 s. This matches quite well with the variation of the soft-soil thickness as shown in Figure 4, which suggests that the thickness of soft clay in these areas ranges from 15 m to 20 m. The Bangkok metropolitan area also has a considerably long predominant period, longer than 0.8 s. The predominant period decreases towards the north and the period reduces to below 0.4 s near Ayutthaya, which is located about 80 km from central Bangkok. The period also decreases towards the east and west directions.

According to the variation of the predominant period of the ground, the greater Bangkok area is classified into four zones as follows:

  (a) Zone I – period less than 0.4 s
  (b) Zone II – period ranging from 0.4 to 0.6 s
  (c) Zone III – period ranging from 0.6 to 0.8 s
  (d) Zone IV – period longer than 0.8 s

The *H/V* spectral ratios for the sites in the different zones are shown in Figure 11. The variation of the predominant period of ground in the greater Bangkok area is shown in Figure 12. The proposed four period ranges were taken from the highway bridge code of Japan [23].
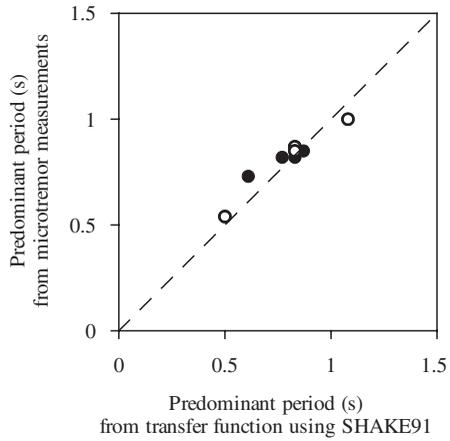
○ from estimated Vs profile ● from measured Vs profile

Figure 10. Predominant period from the microtremor observation and SHAKE91.
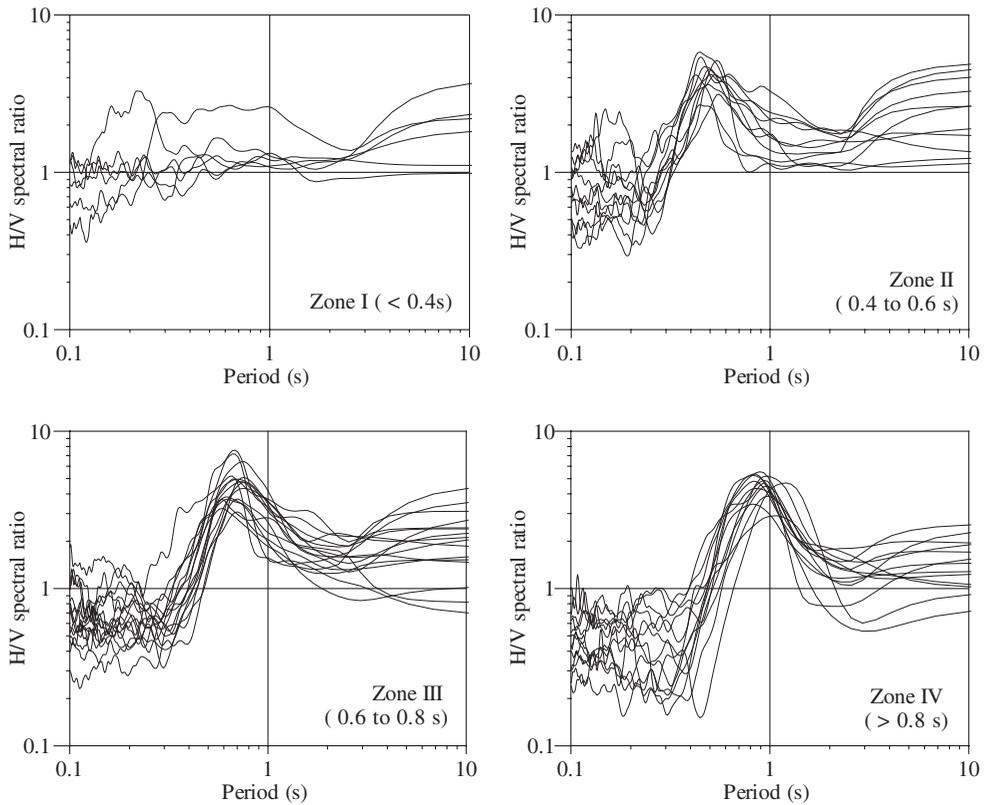
Figure 11. *H/V* spectral ratio of microtremor for sites in the four zones, based on the predominant period.

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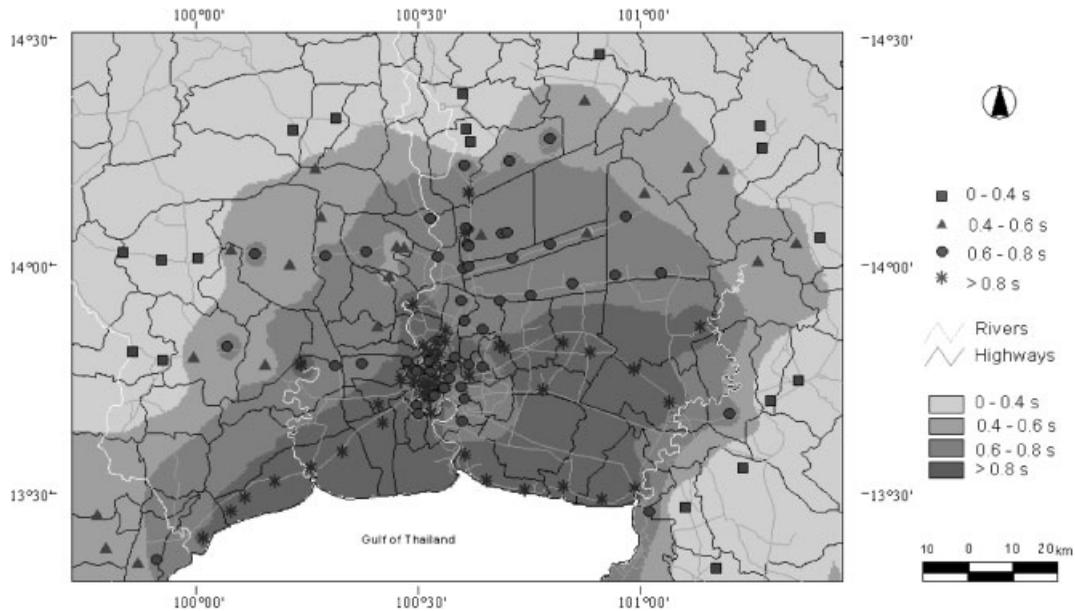
Figure 12. Microzonation of the greater Bangkok area on the basis of variation of the predominant period.

CONCLUSION

In this study, microtremor measurements were carried out at more than 150 sites in the greater Bangkok area. The predominant periods of the sites were obtained using the horizontal-to-vertical spectral ratio (H/V) method. The study showed that the predominant period varied from considerably high values, ranging from 0.8 s to 1.2 s, near the Gulf of Thailand, to low values, less than 0.4 s at the boundary of the plain. On the basis of variation of the predominant period, the greater Bangkok area was classified into four zones. Moreover, the transfer functions were calculated for the eight sites using SHAKE91. Good correlation of the predominant periods obtained from the microtremor analysis and the results from SHAKE91 validated the reliability of the H/V method. The predominant periods obtained from the microtremor observations are also found to correlate well with the characteristic site periods obtained for the soft-soil deposit in the greater Bangkok area using a simple two-layer soil model.

This study shows that there is a possibility of long-period ground vibration in Bangkok, especially in the areas near the Gulf of Thailand. This could cause severe damage to the long-period structures such as high-rise buildings and long-span bridges. Hence, special attention should be given towards the seismically resistant design of such structures.

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