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EVALUATION OF SEISMIC SITE EFFECTS FOR BANGKOK DEEP BASIN

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ABSTRACT

In this study, seismic site effects of Bangkok focusing on deep basin structures are investigated. In the first part, shear wave velocity profiles from surface to bedrock of 16 sites were explored by microtremor array measurement with Spatial Autocorrelation method. The shear wave velocity of sedimentary layers exhibits low value as the average from the surface to 30-m depth is less than 180 m/s and the inferred depth of bedrock varies from 550 to 800 m. In the second part, equivalent linear analysis of the studied sites were conducted in order to examine the ground response and to propose seismic zonation accordingly. The input ground motions were selected and scaled to have response spectra matched with the conditional mean spectrum at several periods. The results of spectral accelerations (Sa) from deep basin models were discussed with the former models having shallow structures. Deep basin effects on long period Sa were indicated. Finally, seismic zonation was proposed based on the design Sa. The distinction between the zones is mainly from the long period effects at 2 second.

INTRODUCTION

It has been well understood that local site conditions can substantially influence the characteristics of ground shaking such as amplitude, frequency content, duration, and earthquake damages. Generally, the local site effects are taken into account for seismic design by classifying site into categories based upon the geotechnical properties of the site related to their dynamic properties. Different levels of design ground motion are provided accordingly. The common practice focusing on the average shear wave velocity from the surface to 30-m depth (Vs_{30}) has been established as a tool for site classification in several international standards for seismic design. However, Vs_{30} which is a good proxy for a shallow site may not be applicable in case of deep basin site. The amplifications of long period ground motion could be greatly influenced by dynamic properties of soil at deeper level.

In Bangkok, Thailand, long period ground motion amplifications from site effects have been occasionally observed from the potential seismic sources located in the northern and western parts of the country and highly active earthquake belts of the Sumatra fault system and subduction zone. The city is situated on a large plain with thick alluvial sediments of the Chaophraya Basin known as Bangkok clay. The subsoil consists of the layer of weathered crust underlain by soft to very soft clay. At deeper strata, alternate layers of sand and stiff clay exist. The depth of bedrock is estimated to be several hundreds meters, but there is no sufficient data available at present. Recent studies indicated that the shear wave velocity is very low from very soft sedimentary layers. The problem of soil amplification of ground motions in Bangkok is, therefore, necessary to be scrutinized for seismic hazard assessment. Up to the present time, only shallow velocity structures of subsoils are available in

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Bangkok area and the depth of bedrock is not known. From lacking of understanding of the velocity structure especially at deep level, this research aims to explore such information for Bangkok and investigate the amplification characteristics resulted from site effects. The economical means of array microtremor observation employed in the study is the Spatial Autocorrelation (SPAC) technique (Aki 1957, Okada 2003). Total 16 sites are explored for shear wave velocity profile down to about 1 km. Seismic site response analyses are conducted using the one-dimension equivalent linear method and the results of different ground response are presented.

GEOLOGY OF BANGKOK

Bangkok is located on the central part of a large lower plain known as Chao Phraya basin. The plain consists of deep Quaternary deposits originated from the sedimentation at the delta of the rivers and marine deposits. Generally, subsoil is relatively uniform throughout the metropolitan. Soil underlying this area can be described as alternating layers of clay and sand. The uppermost layer of weathered crust exists down to the depths of one to five meters. The second layer is soft clay with very low shear strength, and is commonly referred to as soft Bangkok clay.

The thickness of this layer is 15 to 20 meters in the central area, increasing gradually towards the Gulf of Thailand in the southerly direction, and decreasing more rapidly towards the north. The soft clay is underlain by the first stiff clay and subsequently by layers of the first sand, the second stiff clay, and the second sand respectively. From deep borehole investigations, the depth of bedrock is estimated to be in an order of 500 meters or deeper, but there is no sufficient data available at present (AIT 1981). Recent investigations on site characteristics by microtremor observations revealed that Vs_{30} ranges from 100 to 180 m/s (Poovarodom and Plalinyot, 2013).

ASSESSMENT OF SITE CHARACTERISTICS BY MICROTREMOR OBSERVATIONS

Site characteristics, especially the shear wave velocity, are measurable in the field by several practical means which include borehole seismic tests (down-hole, up-hole, and cross-hole test) and surface geophysics tests (reflection, refraction survey). These methods have major drawbacks as they are costly, time consuming and rather difficult to be conducted in urban areas. Recently microtremor observation techniques have been evolved as a more practical technique for exploration of site characteristics. The techniques have major advantages such as economical, environment friendly for urban area and possible for deep structure investigation. This study applied the technique of array microtremor measurement with Spatial Autocorrelation (SPAC) analysis method (Aki, 1957, Okada, 2003) for exploration of phase velocity characteristics and the subsequent shear wave velocity profile from inversion analysis. The field experiments with large array size of hundreds of meters were conducted in order to acquire deep structure formation.

The fundamental concept of SPAC method is to simultaneously record the vertical component of microtremors for several positions in the survey area to obtain Rayleigh wave samples propagating from a wide range of azimuthal angles. The coherency spectrum can then be computed for any pair of sensor in the array to evaluate the correlation among them and to determine phase velocity characteristic which is dispersive. The coherencies for all measurement pairs having the same spatial distance are then azimuthally averaged to provide the spatial autocorrelation coefficients of inter-station distance. By assuming that, the wave energy propagates with only one velocity at each frequency, it can be shown that the measured spatial autocorrelation coefficients for a circular array are fitted to $J_0\left(\omega r/c(\omega)\right)$. Where r is the distance between sensors, ω is the frequency of detected wave, J_0 is the Bessel function of the first kind with the zero-th order and c is the (dispersive) phase velocity for the Rayleigh waves with the fundamental mode. From the dispersion relation of phase velocity and frequency, the results from field observations are then compared with those derived theoretically from a horizontally layered earth model by iteration procedure. The results of best-fit shear wave velocity–depth profile can be determined from the inversion analysis (Yokoi 2005).

Field Works of Microtremor Observation

The measuring system consists of four units of highly sensitive, servo velocity sensors having frequency range of 0.1 to 70 Hz, and acquisition instruments with 32 bits A/D converter. Time synchronisations between each unit were enabled by GPS clock. Before conducting measurements, a huddle test was performed to check the coherency of amplitudes and phase differences between the sensors. The applicable range of frequency for the equipment was identified as from 0.4 to 20 Hz.

The arrangement of sensors for the SPAC observation was an equilateral triangular array with one unit placed at the center of a circle and the other three on its perimeter. Five different sized array arrangements were set at each site with radius (r) of 5, 30, 100, 250 and 340 m. In addition, pairs of the peripheral stations with inter-station distance $\left(\sqrt{3}r\right)$ of 9, 52, 173, 433 and 589 m were also included for calculating the SPAC coefficients. It was suggested that the maximum modeling depths for which shear wave velocity could reasonably be calculated is about half of the longest measured wavelength (Park 1999). In the following results, the longest wavelength from observation taken from the phase velocity of 1,800 m/s and at the frequency of 0.44 Hz. is greater than 4,000 m. Therefore, the maximum depth for inversion analysis in this study is conservatively set at 1000 m.

Data Interpretation

The following discussion analyses representative results for shear wave velocity profile from the recorded microtremor data. Measurements were taken for at least 40 minutes with a sampling frequency of 100 Hz for each set of recordings, producing 240,000 data points, which were then divided into 58 segments of 4096 data points to be used in the analysis. Representative examples of SPAC analysis for the site are shown in Figure 1. In these results, Figure (a) shows an arithmetic mean of the SPAC function from the autocorrelation functions with the interstation distance of 5 m obtained from three pairs of sensors. The analysis was repeated for other distances resulting in the SPAC coefficients shown in Figure (b), where the smaller arrays have SPAC coefficients between the first peak and the first zero crossing in a higher frequency range than those of larger arrays. From these SPAC coefficients, the dispersive phase velocity at a particular frequency was obtained as the argument of the Bessel function, and the results are shown in Figure (c) for different arrays. Selection of an appropriate frequency range for the final dispersion curve was done in the lower-right area of the straight lines of the wavelength being five times the array size (Morikawa et. al. 2004). For example, the phase velocity from the 30-m distance can be selected with confidence in the frequency range higher than 2 Hz. The final dispersion curves are then plotted in Figure (d). Finally, the inversion analysis was performed to search for the optimal velocity structure models fit to the observed dispersion curves. The solutions of dispersive phase velocity from inversion analysis are shown as solid lines in Figure (d).

The results of Vs are presented as two groups after subdividing the studied area into two different zones, A and B, according to similarity of spectral accelerations obtained in the following section. Table 1 summarizes the results of the average shear wave velocity from the surface to depth of 30, 100, 300 and 500 m. The average values for each zone are provided at the end of the Table. From these results, Vs30 of all sites are less than 180 m/s and the observation sites in Zone B exhibit lower average Vs from surface down to 300 m depth. Below this level, influence of Vs of the upper deposits become less pronounced as the value of Vs500 in two zones are almost the same.

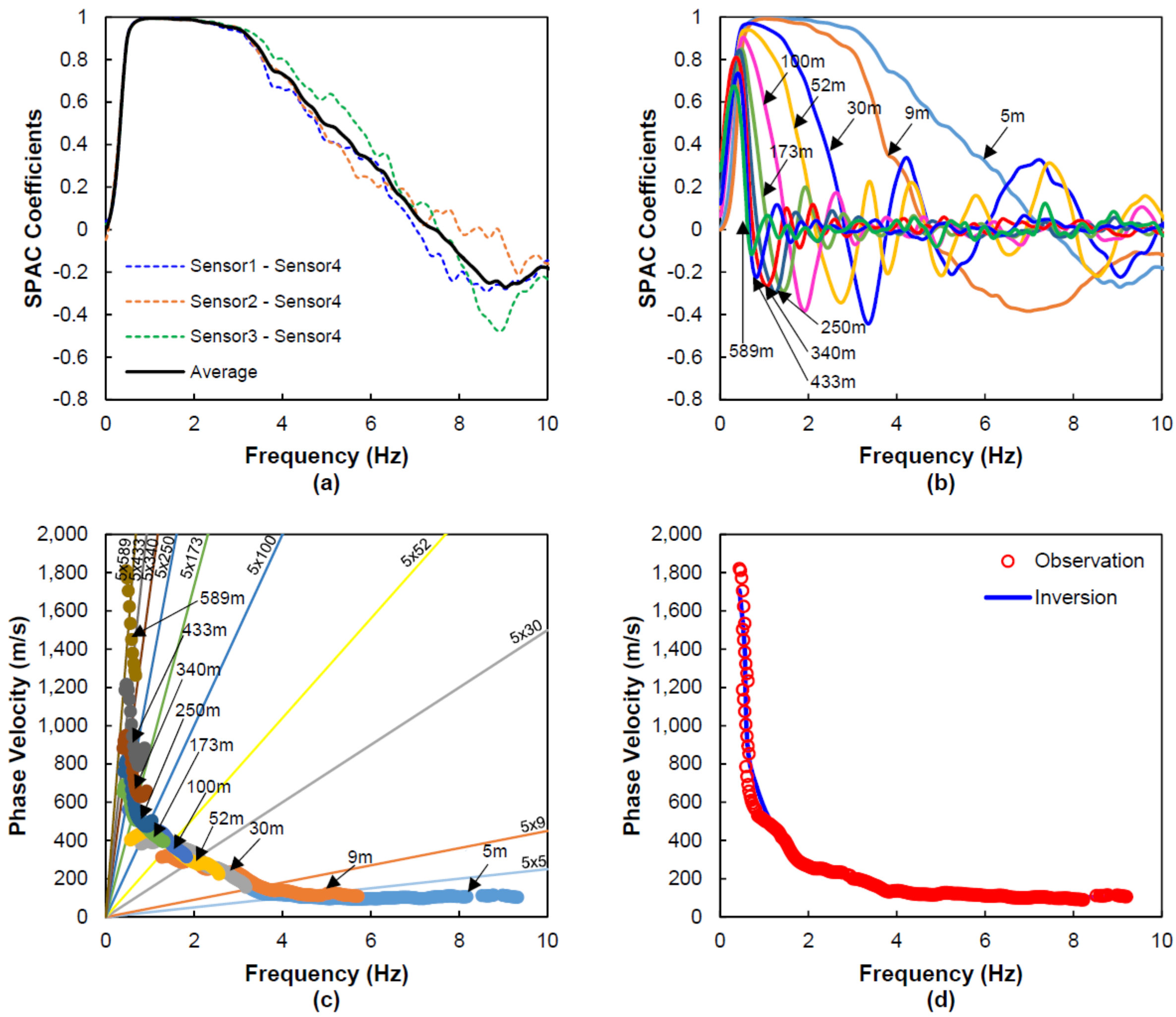
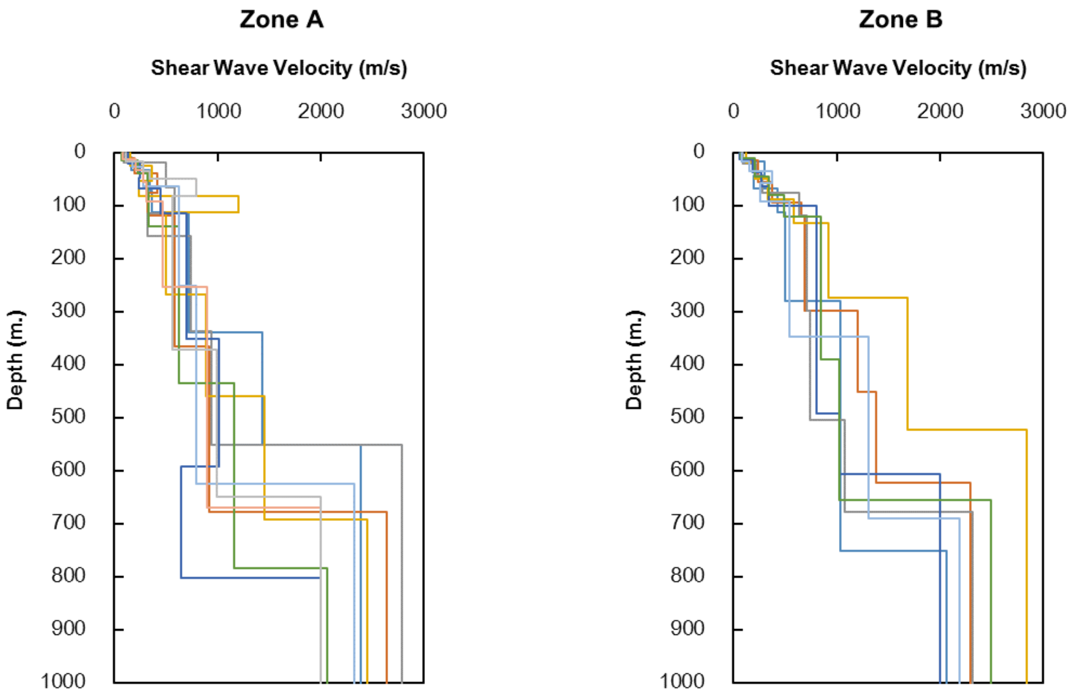


Figure 1. Example of SPAC analysis; (a) SPAC coefficients for 20-m array, (b) SPAC coefficients for all arrays, (c) dispersion curve for each array, and (d) final dispersion curve

Table 1. Result of average shear wave velocity for 16 sites

Site	Vs30 (m/s)	Vs100 (m/s)	Vs300 (m/s)	Vs500 (m/s)
A1	128	225	407	554
A2	137	232	374	471
A3	142	267	420	558
A4	174	268	413	535
A5	161	240	420	525
A6	115	206	349	442
A7	145	259	434	529
A8	126	212	353	466
A9	155	308	443	536
B1	123	204	343	469
B2	106	201	384	476
B3	141	225	448	635
B4	126	220	403	552
B5	103	187	382	483
B6	115	210	410	529
B7	103	189	333	452
Ave. Zone A	**143**	**246**	**401**	**513**
Ave. Zone B	**117**	**205**	**386**	**514**

The final results of shear wave velocity profiles of 16 sites are shown in Figure 2. Generally, Vs of the first 100 m deposits are less than 500 m/s. The velocity increases gradually along depth and the underneath layers of stiffer soil exhibit moderate Vs of about 1000 m/s. There are clear contrasts of shear wave velocity in which the velocity changes abruptly to be about 2000 m/s or more. The depth of such high contrast in velocity varies from 550 m to 800 m inferring the level of bedrock for each site. The results of deep velocity structure to bedrock enable investigation on the effects of deep basin by ground response analysis in the following discussion.



(a) (b)

Figure 2. Shear wave velocity profile for 16 observation sites; (a) Zone A, and (b) Zone B

GROUND RESPONSE ANALYSIS

In order to evaluate seismic site effects, ground responses at the site are analyzed by one-dimension analysis using SHAKE computer program (Schnabel et.al. 1972). From the fact that subsoil in Bangkok is generally uniform and the basin is deep and large, soil columns were modeled as a series of homogenous, viscoelastic infinite horizontal layers with the observed values of shear wave velocity profile. The subsoil layers were subjected to vertically incident shear waves. Computation algorithms are based on continuous solution of wave equation modified for the use with transient motions through the Fast Fourier Transform (FFT) algorithm.

Equivalent linear analysis takes into the account the soil non-linearity by the use of strain compatible shear modulus and damping ratio in a sequence of linear analyses through an iterative process. The output of the analysis provides transfer functions of the site indicating the fundamental periods of the deposits, acceleration time-histories of ground response and response spectrum for a suite of input motions.

In the equivalent linear analysis procedures, the nonlinearity of the shear modulus and damping of soil is accounted for by the use of equivalent linear soil properties using an iterative procedure to obtain values for modulus and damping compatible with the effective strains in each layer. Average relationships between the dynamic shear moduli and damping ratios of soils, as functions of shear strain and static properties, have been established for various soil types. In this study, the relationships for Bangkok clay down to 13.5 m depth were taken from Shibuya and Tamrakar (2003) for the shallow layers. For deep structures, alternate layers of sand and clay having different plasticity index were modeled according to the representative data from boring log. The selected relationships for soil layers are presented in Table 2, and the modulus reduction and damping curves are shown in Figure 3.

Table 2. Dynamic soil properties for equivalent linear analysis

No.	Depth (m)	Material Type	Dynamic Soil Properties
1	0 - 5.5	Clay	Shibuya and Tamrakar 2003
2	5.5 - 10.3	Clay	Shibuya and Tamrakar 2003
3	10.3 - 13.5	Clay	Shibuya and Tamrakar 2003
4	13.5 - 20	Clay	Vucetic and Dobry 1991
5	20 - 35	Sand	Seed and Idriss 1970
6	35 - 50	Clay	Vucetic and Dobry 1991
7	50 - 75	Sand	Seed and Idriss 1970
8	75 - 85	Clay	Vucetic and Dobry 1991
9	85 - 100	Sand	Seed and Idriss 1970
10	100 - Bedrock	Sand	Seed and Idriss 1970
11	Rock	Rock	Schnabel 1973

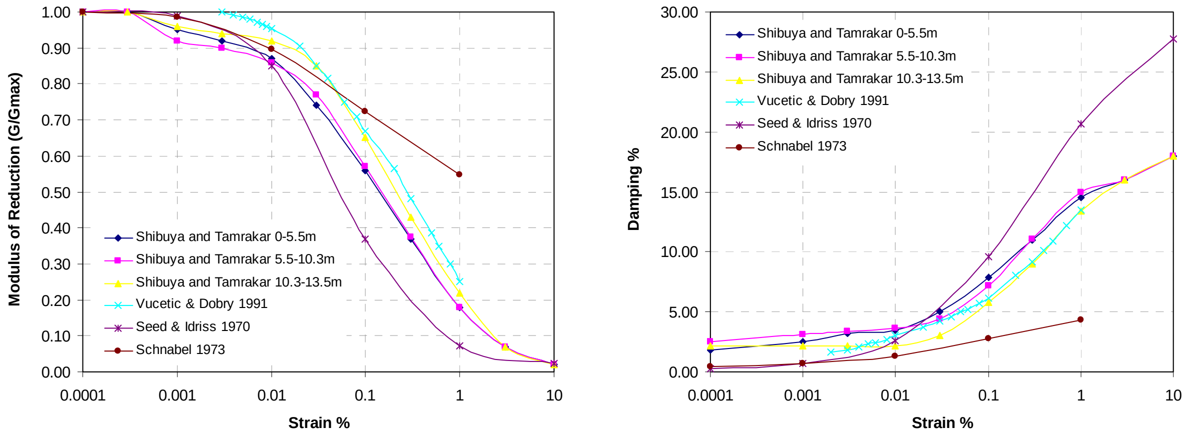


Figure 3. Dynamic properties of subsoil; (a) modulus reduction, and (b) damping

<u>Results of ground response analysis</u>

The ground motions obtained from Probabilistic Seismic Hazard Assessment (Ornthammarath and Warnitchai 2014) were input as rock outcrop acceleration time history and the propagations through the model of soil profile were analyzed by the equivalent linear analysis. The input ground motion were scaled and selected from strong ground motion having response spectra matched with the conditional mean spectrum at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 s, for 2475 years return period. For each period of target spectra matched, six ground motion accelerations are considered and the following discussions present their average results. Figure 4 shows the average acceleration response spectra (Sa) at rock outcrop of input ground motions used in this study.

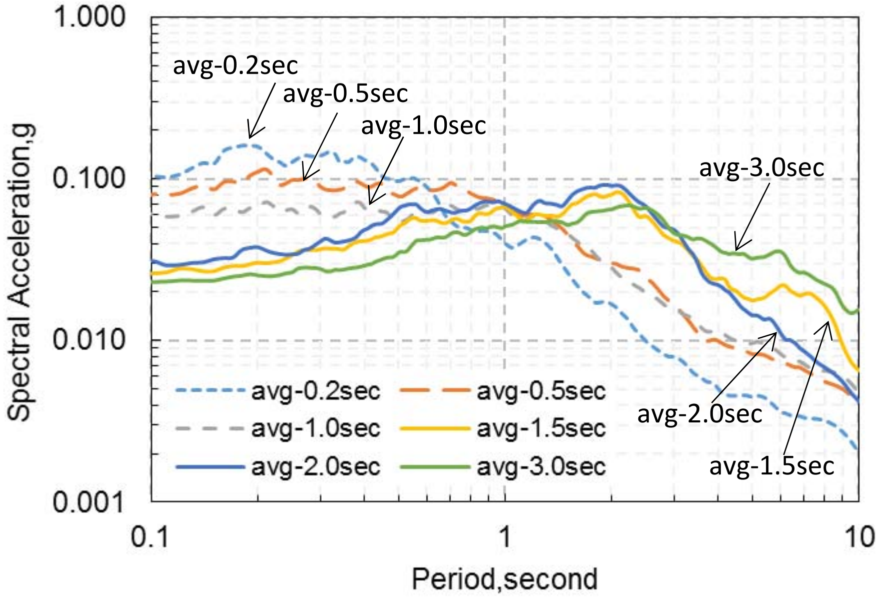


Figure 4. Average spectral response acceleration at rock outcrop of input ground motion matching with the conditional mean spectrum at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 s

From 6 ground motion accelerations of each target period spectrum, the average value of Sa for 5% structural damping were calculated. Then the average Sa were used to evaluate the Maximum Credible Earthquake (MCE) design spectrum for each site. The following example demonstrates the results of the center of business area having largest numbers of high rise buildings in Bangkok, site number A2.

In Figure 5, thin lines are the average Sa resulted from each target period spectrum and their envelop was considered as the design spectrum, shown as a solid thick line. The design Sa exhibits amplifications in wide range of periods. The long period effects are clearly indicated for the period up to 3 seconds. In the former investigation based upon limited information of deep soil structures, engineering bedrock with Vs = 900 m/s was assumed at three different depths, at 80 m, 160 m and 300 m (Ashford 2000). The results of Sa obtained from the same analysis procedures are shown as dash lines for different engineering bedrock level in Figure 5. Comparing with the present results, it is clear that information of deep structures are important as Sa at long period is increased significantly from the former assumptions. The long period amplifications in this zone indicate a potential risk from remote earthquake which can resonate with tall buildings having natural period in this range.

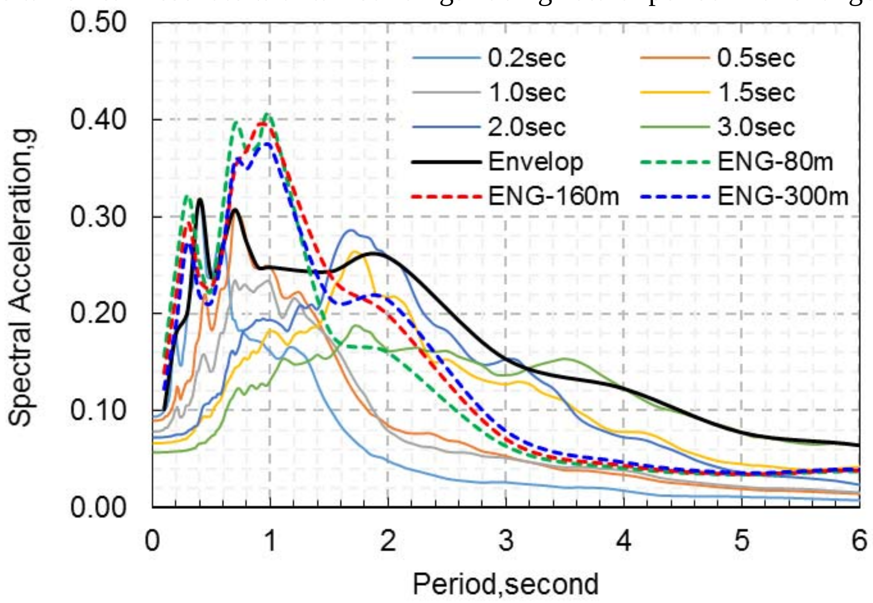


Figure 5. Average spectral response acceleration at surface for input ground motion matching with the conditional mean spectrum at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 s

The results of Sa for all sites were considered for their similarity and the area is divided into two zones having the plots shown in Figure 6 and 7 for zone A and B, respectively. In these Figures, Sa of each site is plotted as a thin line and the average is plotted as a thick line. Comparison of the average design spectrum of the two zones is shown in Figure 8. The distinction between these zones is mainly from the long period effect of 2 second. Finally, seismic microzonation map based on the design Sa for Bangkok is presented in Figure 9. The major parts of Bangkok are described by zone A in which the MCE design Sa is moderate in the range of dominant period from 0.5 to 3 second. In zone B, there exists high Sa at the period about 2 second.

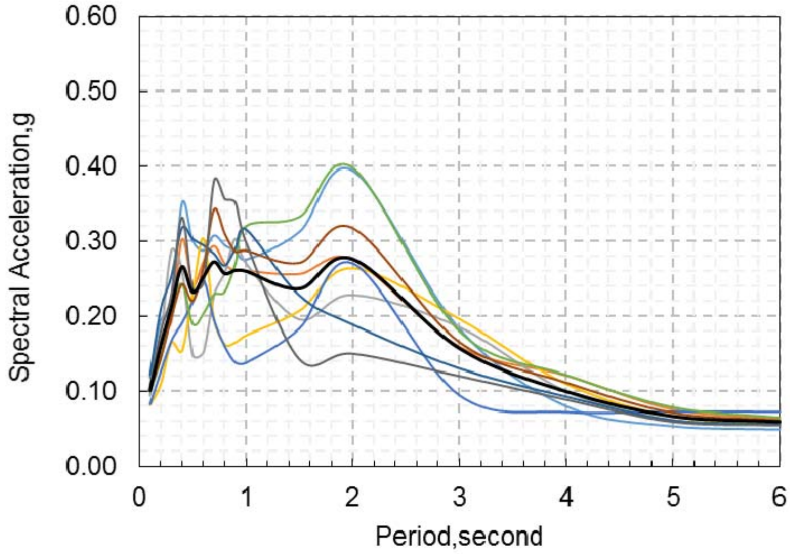


Figure 6. Sa of the observation sites (thin lines) and their average (thick line) in zone A

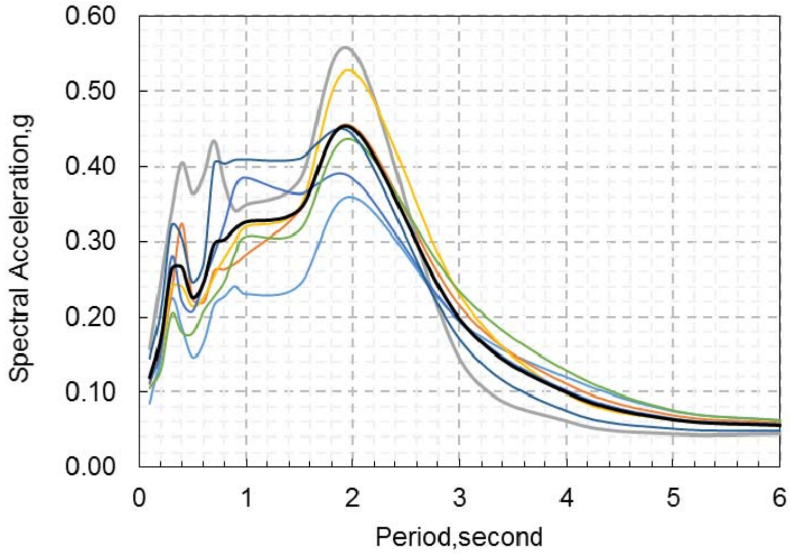


Figure 7. Sa of the observation sites (thin lines) and their average (thick line) in zone B

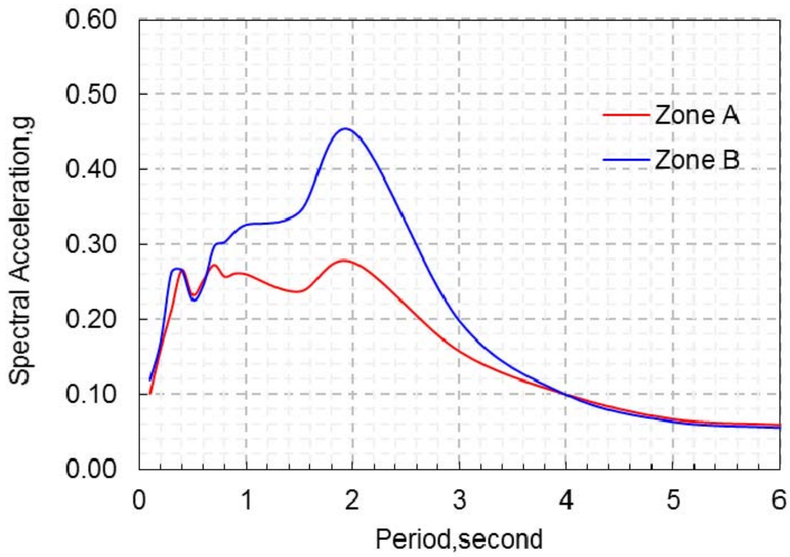


Figure 8. Comparison of the average Sa for zone A and zone B

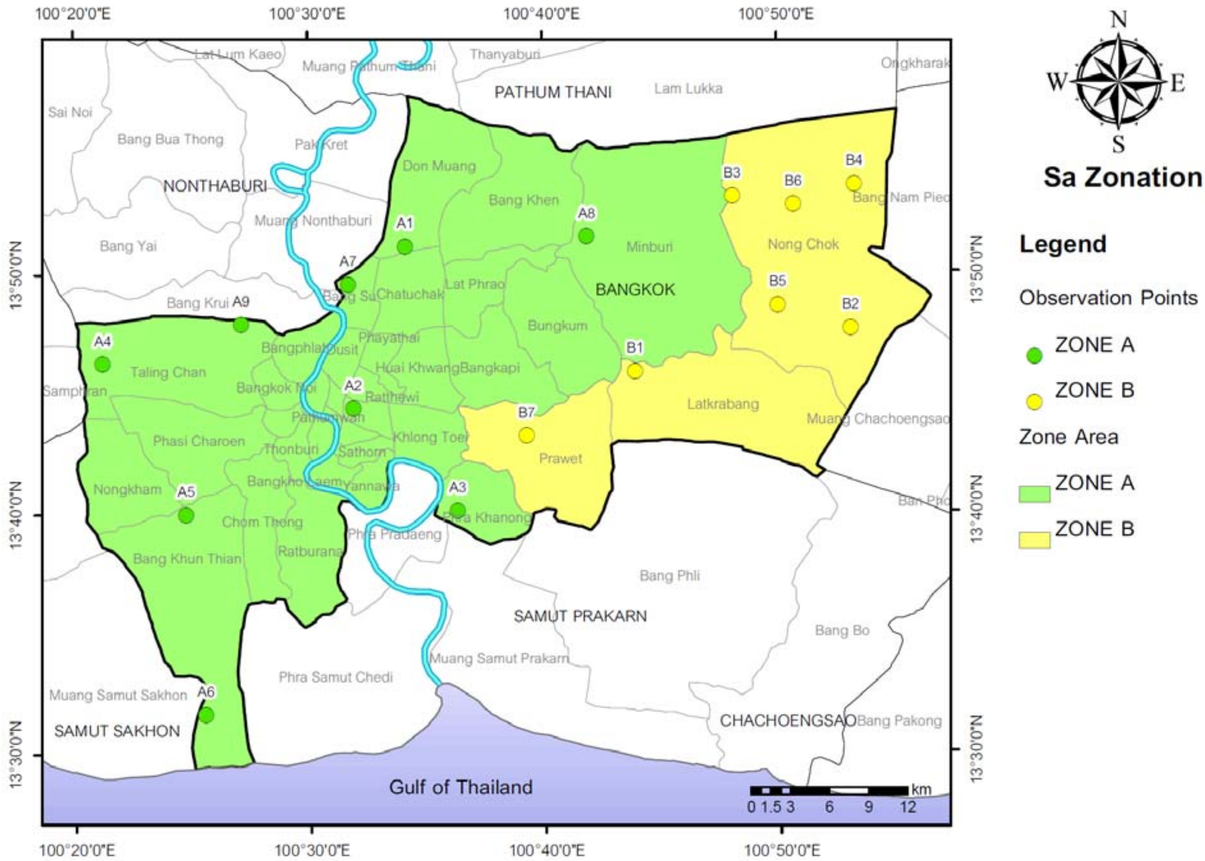


Figure 9. Seismic zonation map of Bangkok from Sa

CONCLUSIONS

Seismic site effects of Bangkok deep basin were evaluated by site investigation and ground response analysis in this study. Following remarks can be drawn from the study.

- Shear wave velocity profiles of 16 sites were explored down to bedrock level by microtremor technique. This exploration demonstrates an applicability of microtremor technique with long period component for deep sedimentary layers.

- Vs30 of all sites are less than 180 m/s, and depth of bedrock varies from 550 m to 800 m. The eastern area of Bangkok exhibits relatively lower average Vs from surface to 300 m depth.
- The design Sa exhibits amplifications in wide range of periods. The long period effects are clearly indicated for the period up to 3 seconds. This finding result differs significantly from previous investigation based on relatively shallow models. The information of deep structures plays an important roles in long period Sa.
- The different characteristics of the spectral accelerations are the key information for seismic microzonation study of Bangkok. Seismic zonation for Bangkok was proposed based on the design Sa. The distinction between these zones is mainly from the long period effects at 2 second.
- The long period amplifications in this zone indicate a potential risk from remote earthquake which can resonate with tall buildings having natural periods in this range.

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