16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 2141

Registration Code: S-H1464319709

DEVELOPMENT OF NEW DESIGN SPECTRAL ACCELERATIONS FOR BANGKOK CONSIDERING DEEP BASIN EFFECTS

N. Poovarodom[(1)], A. Jirasakjamroonsri[(2)], and P. Warnitchai[(3)]

[(1)] *Associate Professor, Thammasat University, Thailand, pnakhorn@engr.tu.ac.th*
[(2)] *Doctoral Student, Thammasat University, Thailand, amorntep_aj@hotmail.com*
[(3)] *Professor, Asian Institute of Technology, Thailand, pennung.ait@gmail.com*

Abstract

In this study, seismic site effects of Bangkok and the vicinity area focusing on deep basin structures were carefully examined in order to establish the spectral accelerations appropriate for design of structures. Investigation of site characteristics was firstly conducted by microtremor observations to explore shear wave velocity profiles from surface to basement rock. The array microtremor technique employed was the Centerless Circular Array (CCA) method, which could provide long detectable wavelength and deep exploration depth. From 100 sites, shear wave velocities analyzed from the observed dispersion curves exhibit very low value at the uppermost level as the average from the surface to 30-m depth was less than 180 m/s in most sites. Generally, shear wave velocity of the first 100 m were less than 500 m/s. The velocity increased gradually along depth and the underneath layers of stiffer soil exhibit moderate value of about 1000 m/s. The estimated depth of basement rock could be inferred from the level having clear contrasts of shear wave velocity. The velocity at this level generally changes abruptly to be about 2000 m/s or more. The estimated depth of basement rock varies from less than 200 m near the boundary of the basin to 800 m in the central area. In the second part, site response analysis was conducted in order to examine the ground response and to propose seismic microzonation accordingly. The ground motions obtained from Probabilistic Seismic Hazard Assessment were input as rock outcrop acceleration time history and the propagation through the model of soil profiles was analyzed by an equivalent linear analysis. From strong motion database, the input motions were selected and scaled to match response spectra with the Conditional Mean Spectrum (CMS) at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 second, for 2475 years return period. Then the average spectral accelerations were used to evaluate the Maximum Credible Earthquake (MCE) design spectrum for each site. The spectral accelerations revealed amplifications in wide range of periods. The results of shear wave velocities and spectral accelerations for neighboring sites were considered for their similarity and the area was sub-divided into three zones consequently. The shapes of the spectral accelerations were the key parameter for seismic microzonation. The proposed zonations were distinct mainly from the amplification at short period of 0.5 second and at long period greater than 1 second.

Keywords: Site effects; Long period amplification; Deep basin; Microtremor; Bangkok.

1. Introduction

Regional economic growth during the past few decades has urbanized Bangkok, the capital city of Thailand, and the vicinity area rapidly. A number of high rise buildings and infrastructures have been constructed in the metropolis with a population more than ten million. The location of Bangkok city is approximately 150 km away from low to moderate seismicity faults and 600 km from highly active Sumatra subduction zone. This area is situated on a large plain underlain by the thick alluvial and deltaic sediments of the Chao Phraya Basin. The top layers of the plain consist of very soft clay, about 15 to 20 m thick in the metropolitan area. At deeper strata, alternate layers of sand and stiff clay exist. The depth of basement rock is estimated to be several hundred meters, but there is no sufficient data available at present. Therefore, the problem of soil amplification of ground motions of Bangkok is susceptible to the long distant earthquakes associated with soft soil amplifications. Tremors have been occasionally observed especially in long period structures even though the earthquake epicentres were located several hundred kilometres away.

Two recent examples of observed site effects from distant earthquake were; (a) magnitude 6.9, 780 km away from Bangkok in 2011 and (b) magnitude 6.3, 720 km away from Bangkok in 2014. Figure 1 shows spectral acceleration of the records from one station in Bangkok (red lines) and another in Surin, located approximately at the same distance but founded on stiff soil (blue lines). Spectral acceleration amplifications in Bangkok are remarkably high especially for period range of 0.6 to 2.5 second, and the second amplification of about 4 to 6 second.

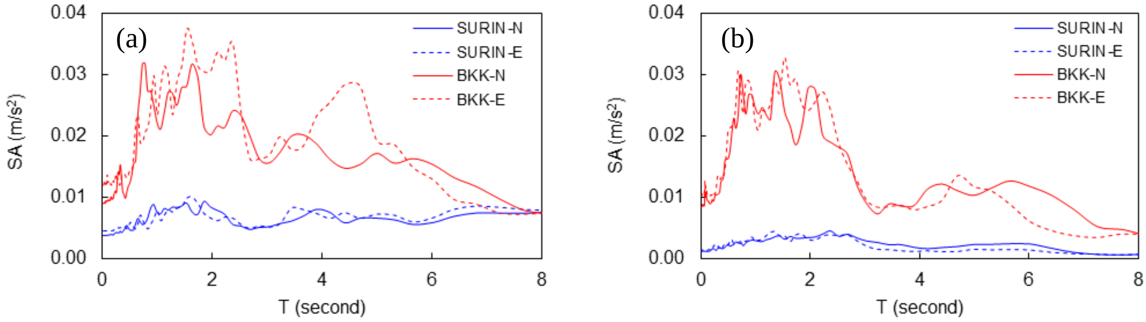


Fig. 1 – Spectral Acceleration in Bangkok (soft soil) and Surin station (stiff soil) (a) 2011 event, (b) 2014 event.

In the current Thai seismic regulations for buildings [1], design spectral acceleration in Bangkok and the vicinity area were developed based on limited information. Site effects from soft soil were taken into account using shear wave velocity (Vs) profiles estimated from field standard penetration resistance of shallow boring log data and assumed basement rock level without proof. The soil layers were modeled accordingly and the spectral acceleration at the ground surface were computed from the propagation of simulated seismic waves, selected to match the Uniform Hazard Spectral for the entire range of periods, through these layers.

In this work, seismic site effects of Bangkok focusing on deep basin structures were studied intensively in order to establish the new spectral acceleration appropriate for design of structures. Investigations of site characteristics were firstly conducted by microtremor observations to explore shear wave velocity profiles from surface to basement rock. The array microtremor technique employed was the Centerless Circular Array (CCA) method (Cho et. al. 2006 [2]), which could provide long detectable wavelength and deep exploration depth. In the second part, site response analysis was conducted in order to examine the ground response and to propose seismic microzonation accordingly. The selected ground motions were obtained from strong motion database and scaled to match response spectra of the Uniform Hazard Spectrum (UHS) with the Conditional Mean Spectrum (CMS) at period from 0.2 to 3.0 second. These ground motion were input as rock outcrop acceleration time histories and the propagations through the model of soil profiles were analyzed by an equivalent linear analysis. Then the average spectral accelerations were used to evaluate the Maximum Credible Earthquake (MCE) design spectrum for each site. The results of spectral accelerations for neighboring sites were considered for their similarity and consequently the area was sub-divided into micro zones.

2. Area of Investigation

Bangkok and the vicinity area is located on the central part of a large lower plain known as the Lower Central Plain or Chao Phraya Plain. The plain is bounded by a mountain range on the west, an upper plain on the north, and Khorat Plateau on the east. It 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 and 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 basement rock at city of Bangkok is estimated to be in an order of 500 meters or deeper, but there is no sufficient data available at present [3]. Recent investigations on site characteristics by small array microtremor observations revealed that Vs30 in Bangkok range from 100 to 180 m/s (Poovarodom and Plalinyot, 2013 [4]). PSHA investigation of the area (Ornthammarath et. al. 2010 [5]) concluded that the major contributors to short- and long-period ground motion hazard in the area are from the nearby active faults (in the northern and western directions) and Sunda subduction zones (in the south-western direction), respectively. It was pointed out that the subduction zone could result in noticeable large expected ground motion at 2 second, emphasizing the important influence of long distance earthquakes.

The area of investigation is located within latitudes 13° 03’ N to 14° 24’ N and longitudes 99° 34’ E to 101° 21’ E, covering Bangkok and the vicinity provinces. Figure 2 shows the location of the investigated area where 100 observation sites are distributed almost evenly inside.

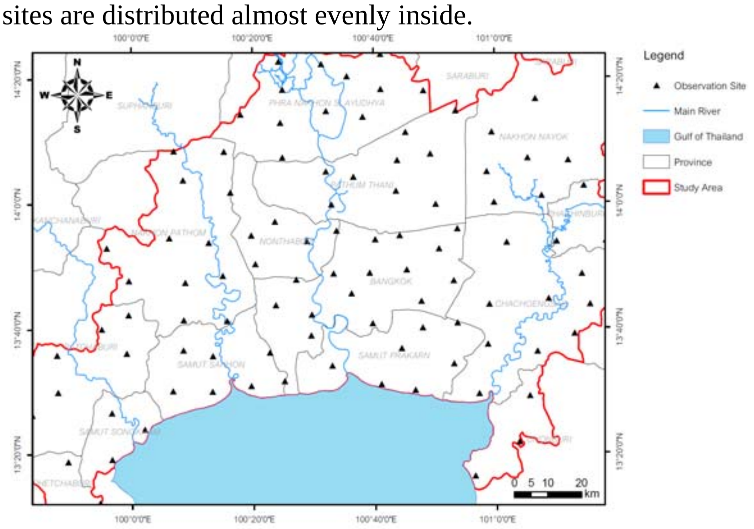


Fig. 2 – Area of study and location of observation sites

3. Microtremor Observation and Analysis

3.1 Centerless Circular Array (CCA) method

Shear wave velocity of the alluvial deposits and depth of the basement rock are the key parameters for site characterization and ground response analysis. At present, techniques for shear wave determination using microtremor observation have become more common from view point of economical, urban friendly and deeper exploration comparing with conventional geophysics methods. One of a widely used microtremor technique is the spatial autocorrelation (SPAC) method which is based on the relationship between the temporal and spatial spectra of waves to obtain phase velocity dispersion curve [6]. This technique uses the record of microtremor data in vertical direction on ground surface. Recently, the Centerless Circular Array (CCA) method has been developed to provide more efficient and accurate phase velocity up to very long wavelength range [2]. Field works require vertical component of microtremor records obtained from circular arrays as same as the SPAC.

This method can yield longer detectable wavelength comparing with the SPAC method as the theoretical spectral ratio for estimation of phase velocity by the CCA method represents to the experimental spectral ratio in better form than only the zero-th order Bessel function in the SPAC method. More specifically, phase velocity from the CCA method can reach to lower frequency range than the SPAC method, thus deeper investigation can be possibly achieved.

The fundamental concept of CCA is based on spectral ratio representations which may be considered as a general case of the SPAC method. The spectral ratio which contains information of phase velocities is an integration of all information on the field of vertical component of microtremors. Since the integration does not distinguish arriving waves with different azimuth angles, this technique could extract higher resolution in long wavelength. Field works require to deploy a circular array of radius r and record the vertical component of microtremor $z(t,r,\theta)$. Define the average value $Z_0(t,r)$ along the circumference and its weighted average $Z_1(t,r)$ as;

$$Z_0(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)d\theta \tag{1}$$

$$Z_1(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)\exp(i\theta)d\theta \tag{2}$$

Assuming that the fundamental Rayleigh wave mode dominates the vertical component of the microtremor field, the ratio of their power spectra densities, denoted by $G_0(r,r;\omega)$ and $G_1(r,r;\omega)$, can be written as;

$$\frac{G_0(r,r;\omega)}{G_1(r,r;\omega)} = \frac{J_0^{\,2}(rk(\omega))}{J_1^{\,2}(rk(\omega))} \tag{3}$$

Where J_0 and J_1 is the Bessel function of the first kind with the zero-th order and the first order, respectively. The wavenumber k, and phase velocity c, are then estimated by fitting the observed spectral ratio with $J_0^{\,2}(rk(\omega))/J_1^{\,2}(rk(\omega))$. The above statement holds in noise-free conditions, where noise is considered as the non-propagating components contained in the field of microtremors. In the general practice where noise is contained, equation (3) can be shown for the case of the fundamental mode dominating as;

$$\frac{G_0(r,r;\omega)}{G_1(r,r;\omega)} = \frac{J_0^{\,2}(rk(\omega)) + \varepsilon(\omega)/N}{J_1^{\,2}(rk(\omega)) + \varepsilon(\omega)/N} \tag{4}$$

Where ε is the noise-to-signal ratio, representing the ratio of the power of the incoherent noise to the power of the coherent signal. Assume that the fundamental mode is dominant, ε can be estimated as;

$$\varepsilon \approx \left(-B - \sqrt{B^2 - 4AC}\right)/2A \tag{5}$$

$$A = -\rho^2, B = \frac{\rho^2}{coh^2} - 2\rho^2 - \frac{1}{N}, C = \rho^2\left(\frac{1}{coh^2} - 1\right) \quad \text{and } coh^2 = \frac{|G_0(0,r;\omega)|^2}{G_0(r,r;\omega)G_0(0,0;\omega)} \tag{6}$$

ρ is the spatial autocorrelation coefficients, and N is the number of sensors along the circumference.

3.2 Inversion of shear wave velocity profile

From the dispersion relation of phase velocity and frequency, the results from field observations were then compared with those derived theoretically from a horizontally layered earth model by iteration procedure. The results of the best-fit shear wave velocity–depth profile were determined from the inversion analysis, in which this study applied the combination of Down Hill Simplex Method with Very Fast Simulated Annealing developed by Yokoi (2005) [7].

3.3 Field works of microtremor observation

The equipment used for microtremor observation consists of four units of highly sensitive, servo velocity sensors having frequency range of 0.1 to 70 Hz, and data acquisition instruments with 32 bits A/D converter. Time synchronization between each unit was enabled by GPS clock with a resolution of 1 /100 seconds. The arrangement of sensors in this study was an equilateral triangular array with one unit placed at the center of a circle and the other three on its perimeter or corners of the triangle. The duration for recording microtremor data was about 40 minutes for each array. Four different sized array arrangements were set at each site with radius (*r*) of 5, 30, 100 and 250 m.

3.4 Analysis of data

The following discussion explains produdures of analysis for phase velocities from the recorded microtremor data. Measurements were taken for 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 example of CCA analysis is shown in Figure 3. Figure 3(a) and (b) show the observed spectral ratio and the ratio of Bessel function as in Equation (4), respectively. By fitting the two functions, the identified f_i and rk_i can be obtained. Phase velocities are then computed by $c_i = 2\pi f_i / k_i$ and shown in Figure 3(c). Their ensemble for different arrays are plotted in Figure 3(d).

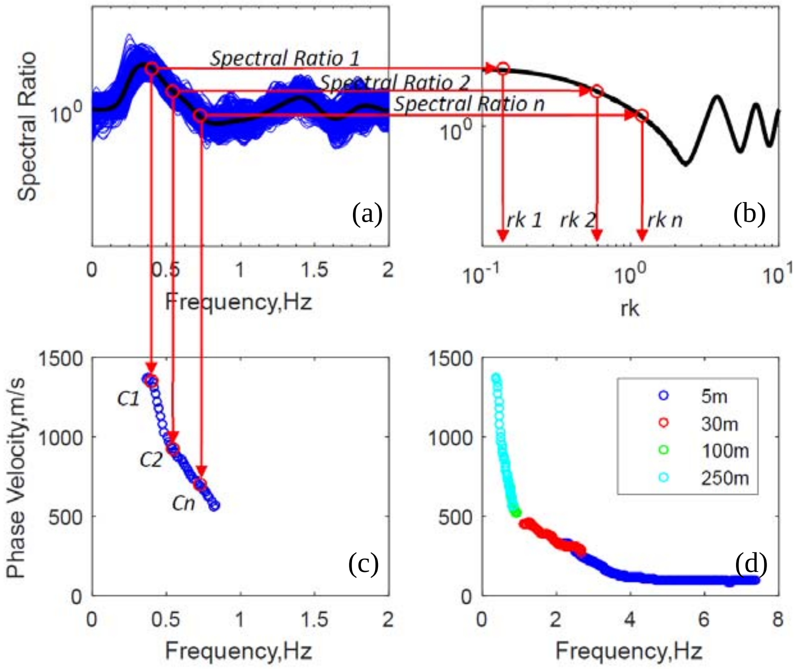


Fig. 3 – Example of CCA analysis; (a) spectral ratio for 250-m array, (b) ratio of Bessel function (c) estimated dispersion curve for this array, and (d) final dispersion curve

Figure 4 (a) and (b) show comparison of the computed wavelength from SPAC and CCA techniques using the same set of data, respectively. Clearly, the CCA method provides longer detectable wavelength and lower frequency range than the SPAC method does. It can be inferred further that better accuracy of inversion analysis of shear wave velocity from phase velocity dispersion can be achieved by the CCA method, especially in deeper structure. The results from other sites also exhibit similar findings. The inversion results are included in these figures as the solid lines. Figure 4 (c) shows examples of the inverted Vs profiles from the result by CCA method using the neighbourhood algorithm [8]. There are several posible solutions with different levels of misfits as shown in color lines, illustrating the problem of non uniqueness of the inversion. The model which has mínimum misfit was selected as the solution of the inversion, and it is shown as the black line in this figure.

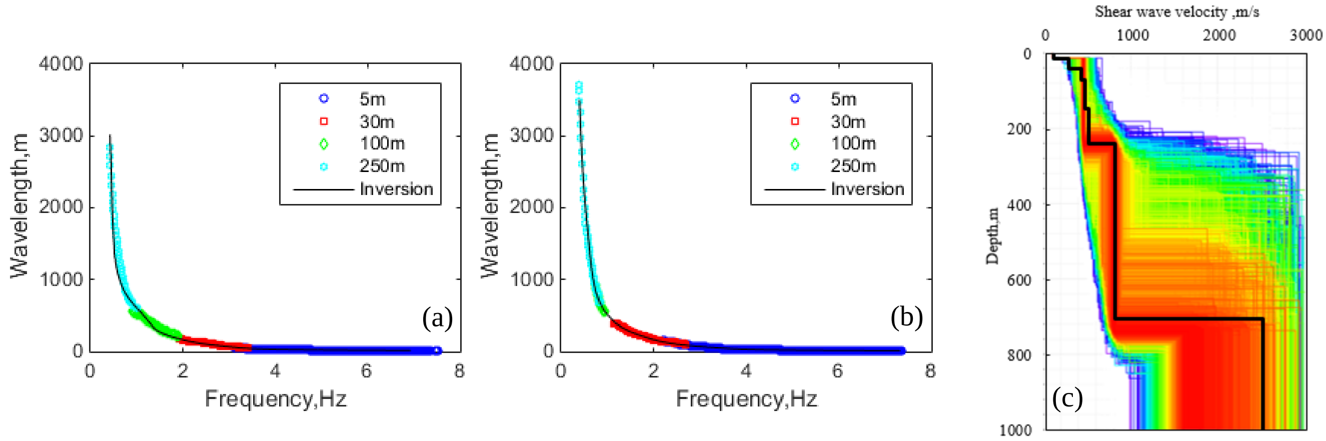


Fig. 4 – (a) Wavelength by SPAC, (b) wavelength by CCA, (c) inverted Vs from CCA.

4. Site Response Analysis

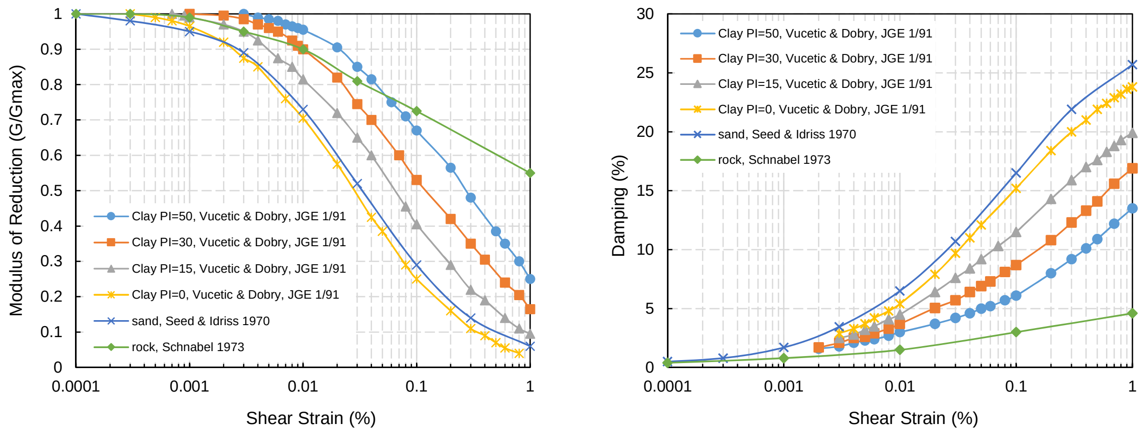
4.1 Equivalent linear analysis

In order to evaluate seismic site effects, ground responses at each site were analyzed from a set of selected input motions propagating through soil models according to the Vs profile. Since the dynamic soil properties in this area are limited to the equivalent linear approach [9, 10], therefore the equivalent linear analysis is only applied in this study. Moreover, for deep basin and gradual slope at the edges, good agreement between the 1-D and 2-D amplifications was observed by several studies [11-13]. Thus the 1-D analysis is considered appropriate due to the fact that subsoil in Bangkok is generally uniform and the basin is deep and large.

In the equivalent linear analysis procedures [14], the 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. The nonlinearity of the shear modulus and damping of soil were taken into accounted by 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. A recent study on the stiffness characteristics at a small strain level of Bangkok Clays [10] found that the stiffness degradation curves fell within the ranges of plasticity index similar to those reported by Vucetic and Dobry (1991) [15]. In this study, the relationships for Bangkok clay down to 100 m depth were selected according to the plasticity index and the representative data from boring log. For deep structure, dynamic properties of sand and rock were taken from Seed and Idriss (1970) [16] and Schnabel (1973) [17], respectively. The selected relationships for soil layers are presented in Table 1 and the modulus reduction and damping curves are shown in Figure 5.

Table 1 – Dynamic soil properties for equivalent linear analysis

No.	Depth (m)	Material Type	Dynamic Soil Properties
1	0-15	Clay PI=50	Vucetic and Dobry 1991
2	15-30	Clay PI=30	Vucetic and Dobry 1991
3	30-60	Clay PI=15	Vucetic and Dobry 1991
4	60-100	Clay PI=0	Vucetic and Dobry 1991
5	100-basement rock	Sand	Seed and Idriss 1970
6	rock	rock	Schnabel 1973



(a) (b)

Fig. 5 – Dynamic properties of soil model; (a) modulus reduction, and (b) damping

4.2 Selected input ground motions

The ground motion parameters were obtained from Probabilistic Seismic Hazard Assessment study [18] considering the effects of possible earthquakes of different magnitudes, occurring at different locations in different seismic sources and at different probability of occurrence. The PSHA results were considered in terms of the Uniform Hazard Spectrum (UHS) at return period of 2475 years (Maximum Considered Earthquake). The UHS was defined at rock outcrop level and the representative ground motions could be artificially simulated by generating ground accelerations having spectrum that match the UHS for the entire range of periods. However, this approach was considered to be conservative as it implies that large-amplitude spectral values would occur at all periods by a single ground motion. The Conditional Mean Spectrum (CMS) [19], was proposed as an alternative to provide the expected response spectrum, conditioned on occurrence of a target spectral acceleration value at the period of interest.

In this study, six sets of input motions were selected from strong motion database having similar seismic mechanisms as in Bangkok area. Then, the ground motions in each set were scaled to match the UHS with the CMS at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 second, for 2475 years return period. For each period of target spectra matched, six ground motion accelerations were considered and their average results are presented in the following discussions. Figure 6 shows the average acceleration response spectra (Sa) at rock outcrop of the selected input ground motions.

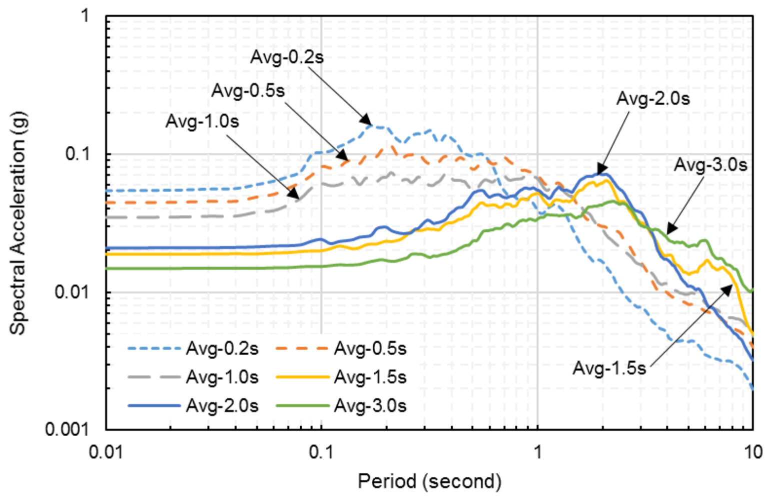


Fig. 6 – Average spectral response acceleration at rock outcrop of input ground motion matching with the conditional mean spectrum at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 s

From these inputs at the rock outcrop acceleration time history, the propagations through the model of soil profile were analyzed by the equivalent linear analysis. Then the average spectral accelerations for 5% structural damping were calculated to evaluate the MCE design spectrum for each site.

5. Results and Discussions

5.1 Shear wave velocity and depth of basement rock

Shear wave velocities (Vs) along depth of each site were derived from inversion analysis of dispersion curves. The top layers of most sites are soft soils in which Vs is very low. Site classifications by the average Vs from the surface to 30-m depth (Vs30) are presented as a map in Figure 7. From this map, variations of Vs30 in this basin can be clearly distinguished as it varies from 100 to 600 m/s. The area with lowest Vs30 is located in the south-east part of the basin where soil contains the deepest layer of soft deposits. Area along the Gulf of Thailand has low Vs30 which is resulted from layers of deltaic sediments. The hardest soil sites in this study are located around the boundary in the north, east and west foothill areas which yields highest Vs30.

Generally, Vs of the first 100 m deposits is 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 can be inferred as the level of basement rock for each site. The results of deep velocity structure to basement rock enable investigation on the effects of deep basin by ground response analysis in the following discussion. The inferred depths of basement rock for all sites are presented as a map in Figure 8. The estimated depth of basement rock varies from 200 or less to 800 meters. The shape of basement rock in the basin can be drawn as a bowl where the boundary of the basin possesses shallower depth comparing with the central area of Bangkok.

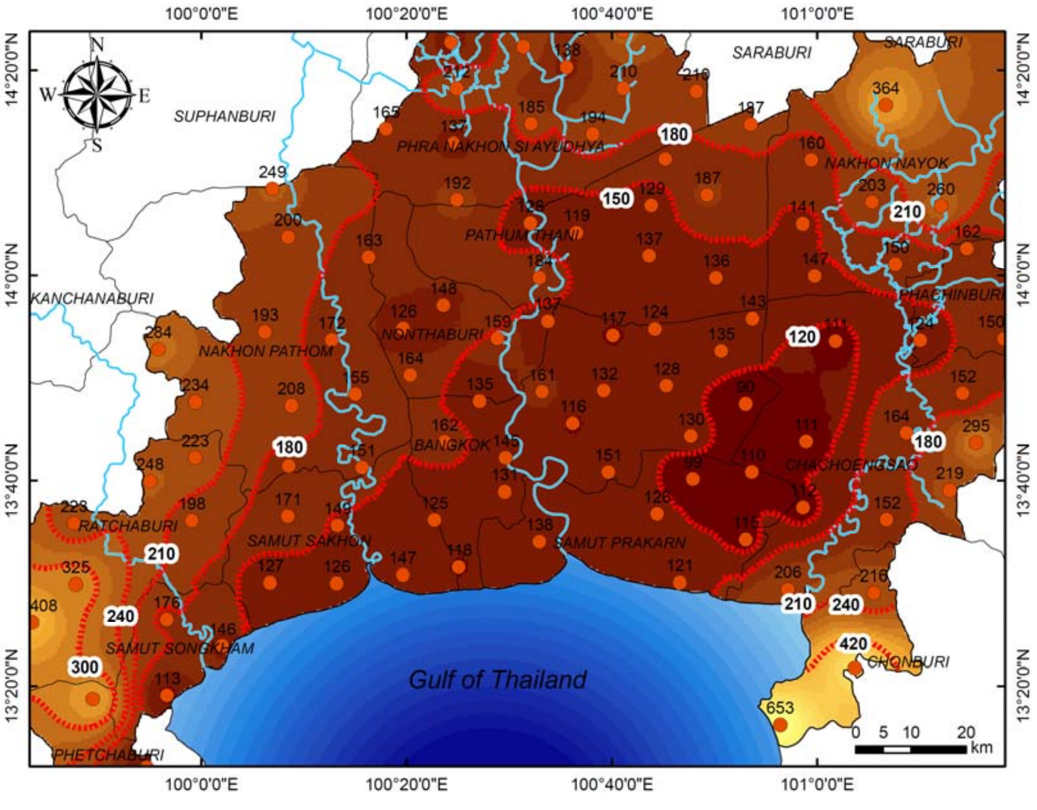


Fig. 7 – Map of Vs30 in Bangkok basin

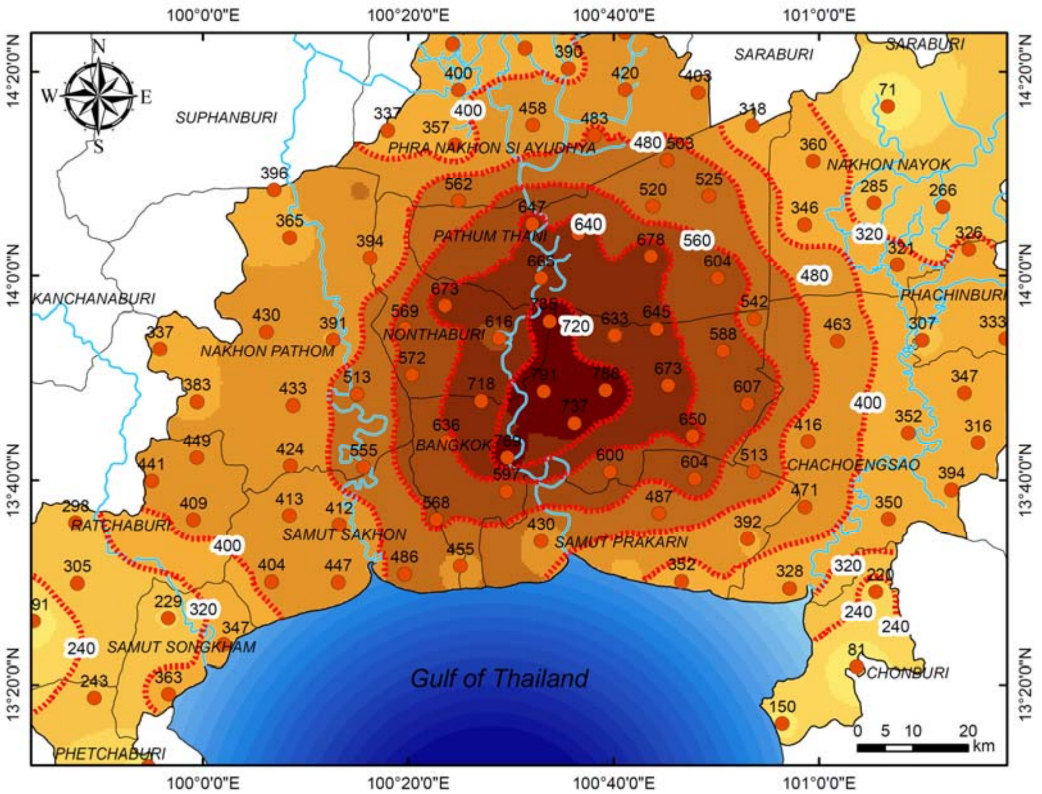
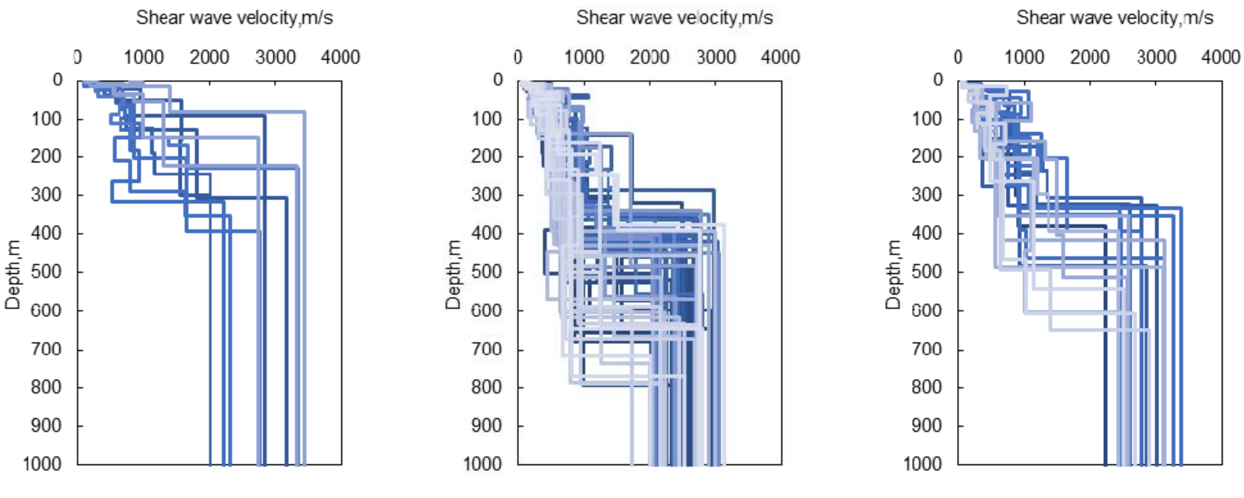


Fig. 8 – Map of depth of basement rock in Bangkok basin

The results of 100 sites were then divided into three groups based on the similarity of profiles including depth of basement rock and their proximity. The areas of these groups will be referred as zone 1 to 3. The shear wave velocity profiles for these zones are plotted in Figure 9.



(a) (b) (c)

Fig. 9 – Shear wave velocity profile in three zones; (a) zone 1, (b) zone 2 and (c) zone 3.

5.2 Spectral acceleration and microzonation map

The following example demonstrates the results of ground response analysis of one site at the central of Bangkok. In Figure 10, thin lines are the average Sa resulted from each target period CMS spectrum and their envelop was considered as the design spectrum, shown as a solid thick line. The design Sa exhibits possible amplifications in wide range of periods. The long period effects are clearly indicated for the period at 1.5 second and longer. To demonstrate the effect of deep basin model of this study, comparisons were made with Sa from shallower soil models used in the past study.

Based upon limited information of deep soil structures, engineering basement rock with Vs = 900 m/s was assumed at three different depths, at 80 m, 160 m and 300 m [20]. The results of Sa obtained from the same analysis procedures are shown as dash lines for different engineering basement rock level in Figure 10. Comparing with the present results, it is clear that information of deep structures is very important as Sa at long period increases significantly comparing with results from the shallow models. 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.

For the three sub-divided zones as described in the previous section, Sa of each studied site was computed and their averages were considered as the representative Sa. The results of microzonation are presented in Figure 11 (a) and (b). Figure 11 (a) shows the zonation map established from the shear wave velocity profiles and results of Sa. Comparison of the average MCE Sa of the three zones is shown in Figure 11 (b). The distinction between these zones is mainly from the short period of 0.5 second and long period effect after 1 second. The western and eastern boundary of the basin where the topography is foothill of mountain ranges are locate in zone 1. In this zone, the shallow Vs is high, as in Figure 7, and the depth of basement rock is shallow, as in Figure 8. The MCE Sa in this zone exhibit very high peak at the short period of 0.5 second, but low value for moderate and long period. Zone 2 covers major area in the central part of the basin. The general Vs profiles in this zone are low and gradually increase with depth and the basement rock levels are relatively deep. Comparing with zone 1, the MCE Sa in zone 2 is drastically lower in short period but higher in long period. In zone 3, the area possesses very low Vs at the shallow level and high contrast with the basement rock at deep basin. This characteristic leads to very high spectral amplification at long period and results in large Sa at the period about 1 second and longer.

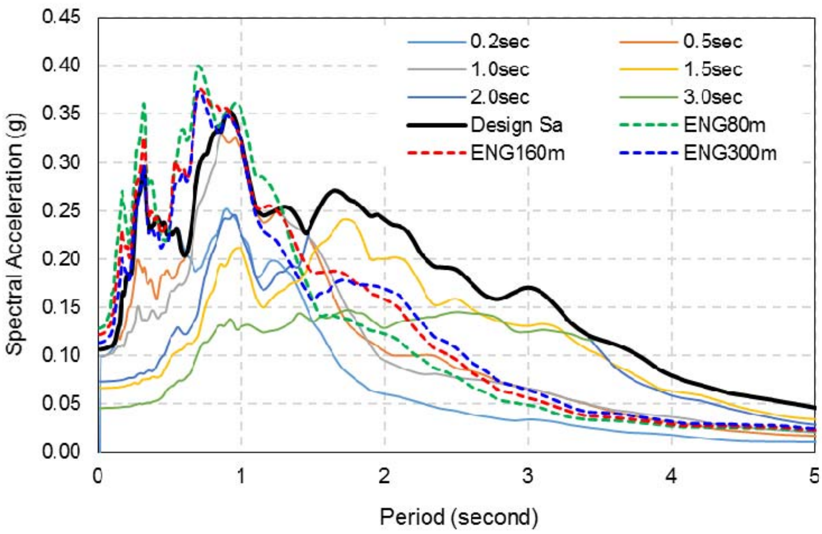


Fig. 10 – Average spectral response acceleration at surface for input ground motion matching with the conditional mean spectrum at 0.2, 0.5, 1.0, 1.5, 2.0 and 3.0 s

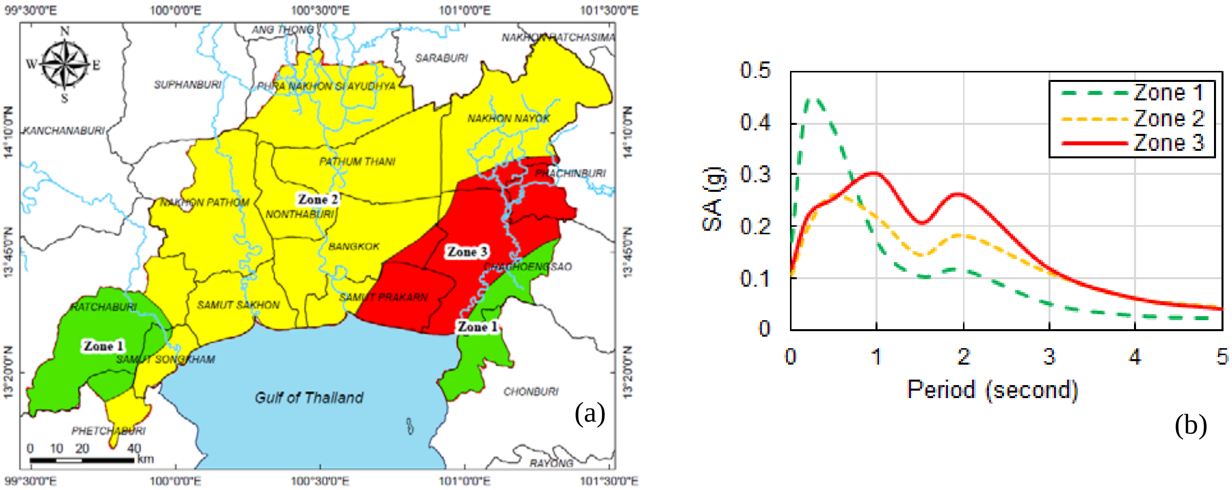


Fig. 11 – (a) Proposed seismic microzonation map of Bangkok (b) The average design Sa for zone 1 to 3

It should be remarked that, the proposed microzonation map is rather similar to the map of Vs30 than the depth of basement rock. This could be resulted from the input ground motions which were constraiend up to 3.0 second because of the assumption of the attenuation models used in the PHSA study. Future deveopment considering longer period ground motions is necessary.

6. Concluding Remarks

This paper presents the development of new design spectral accelerations for Bangkok and the vicinity area considering deep basin effects. The study conducted site investigation by array microtremor observations for soft and deep soil structures, and site response analysis by one-dimension equivalent linear method for spectral accelerations. The following remarks are concluded from the study.

- The Centerless Circular Array (CCA) microtremor technique was successfully applied to explore shear wave velocity down to basement rock for 100 sites of deep basin structures.
- Vs30 in the central area is generally lower than 180 m/s. The area along the Gulf of Thailand and the south-east part exhibit very low Vs30 of about 100 m/s while high Vs30 of 300 to 600 m/s are found near the boundary in the north, the west and the east of the basin.
- The estimated depth of basement rock around the boundary is about 200 m or less. The depth increases gradually into the central area and the deepest part reaches 800 m.
- Applying the concept of the Conditional Mean Spectrum (CMS) to select appropriate input motions for site response analysis, the results of Sa reveal amplifications in wide range of periods. Long period effects can be clearly indicated at the period over 1 second. The information of deep structures plays very important roles in long period amplifications comparing with the models of shallower basin.
- The shear wave velocity profile to basement level and the shape of Sa are the key information for seismic microzonation study of this basin. Seismic zonation was proposed for three zones. The distinction of Sa among these zones is mainly from the short period Sa at 0.5 second and long period greater than 1 second.
- The long period amplifications resulted from the effects of Bangkok deep basin indicate potential risks from distant earthquakes which can resonate with tall buildings having coincided natural periods in this urbanized area. The results from this study are currently considered for the revision of the national seismic design standard.

7. Acknowledgements

This study is supported by the Thammasat University scholarship for a Ph.D. student and the Thailand Research Fund, research number RDG5630018. The sources of support are gratefully acknowledged.

8. References

[1] Department of Public Works and Town & Country Planning (DPT) (2009): Standard for earthquake resistant design of buildings, DPT standard 1302, (in Thai).

[2] Cho I, Tada T, Shinozaki Y (2006): Centerless circular array method: Inferring phase velocities of Rayleigh wave in broad wavelength range using microtremor records. *Journal of geophysical research*, Vol.111, B09315.

[3] AIT (1981): Investigation of land subsidence caused by deep well pumping in the Bangkok area, Asian Institute of Technology, Thailand.

[4] Poovarodom N, Plalinyot N (2013): Site characterization in the Greater Bangkok area by microtremor observations. *Journal of earthquake engineering,* **17**,(2), 209-226.

[5] Ornthammarath T, Warnitchai, P, Worakanchana, K, Zaman, S, Sigbjörnsson, R, Lai CG (2010): Probabilistic seismic hazard assessment for Thailand, *Bulletin of Earthquake Engineering,* **9**(2), 367-394.

[6] Aki K (1957): Space and time spectra of stationary stochastic waves, with special Reference to microtremors, *Bulletin of the Earthquake Research Institute*, No. 22, 415–456.

[7] Yokoi T (2005): Combination of down hill simplex algorithm with very fast simulated annealing method-an effective cooling schedule for inversion of surface wave's dispersion curve, *Proc. of the Fall Meeting of Seismological Society of Japan*. B049.

[8] Wathelet M (2008): An improved neighborhood algorithm: parameter conditions and dynamic scaling. Geophysical Research Letter, 35, L09301, doi: 10.1029/2008GL033256.

[9] Shibuya S. and Tamrakar S.B. (2003), “Engineering Properties of Bangkok Clay”, Characterization and Engineering Properties of Natural Soils. Tan et al. (eds.) Swets & Zeitlinger. Lisse.

[10] Likitlersuang S, Teachavorasinskun S, Surarak C (2013): Small strain stiffness and stiffness degradation curve of Bangkok Clays. Soil and Foundations, 53(4), 498-509.

[11] Kramer L (1996): Geotechnical Earthquake Engineering. Prentice-Hall, Inc. Simon & Schuster / A Viacom Company.

[12] Larkin T, Marsh J (1992): Two dimensional nonlinear site response analyses. Bulletin of the New Zealand national society for Earthquake Engineering, Vol.25, No.3, September 1992.

[13] Murat EH, Recep I (2014): A numerical study on comparison of 1D and 2D seismic response of a basin in Turkey. American Journal of Civil Engineering, 2(5), 123-133.

[14] Schnabel PB, Lysmer J, Seed HB (1972): SHAKE: A Computer program for earthquake response analysis of horizontally layered sites. *Report No. UCB/EERC-72/12*, Earthquake Engineering Research Center, University of California, Berkeley.

[15] Vucetic M, Dobry R (1991): Effect of plasticity on cyclic response. *Journal of Geotechnical Engineering, ASCE*. **117** (1), 89-107.

[16] Seed HB, Idriss IM, (1970): Soil moduli and damping factors for dynamic response analyses. *Report No. EERC-70/10*, Earthquake Engineering Research Center, University of California, Berkeley.

[17] Schnabel PB, (1973): Effects of local geology and distance from source on earthquake ground motions. Ph.D. Thesis, University of California, Berkeley.

[18] Ornthammarath T, Warnitchai P (2014): Action plan for earthquake disaster prevention and mitigation in Bangkok. Report submitted to Bangkok Metropolitan Administration.

[19] Baker JW (2011): Conditional mean spectrum: tool for ground motion selection, *Journal of Structural Engineering*, 137(3), 322-331.

[20] Ashford, S.A. (2000) “Shear wave velocity testing at Chulalongkorn University and SIIT Bangkok, Thailand,” Test Report No. TR-2000/15, University of California, San Diego, Department of Structural Engineering, Structural Systems Research Project.