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Investigation of long period amplifications in the Greater Bangkok basin by microtremor observations

N. Poovarodom

Faculty of Engineering, Thammasat University, Pathumthani, Thailand.

A. Jirasakjamroonsri

Faculty of Engineering, Thammasat University, Pathumthani, Thailand.

ABSTRACT: Bangkok has occasionally experienced long period amplifications of ground motion from remote earthquakes and due to seismic site effects. The subsoil consists of layers of very soft clay and alternate layers of sand and stiff clay at deeper strata. The depth of bedrock is uncertain but it was estimated to be several hundred meters. Since the investigation of long period site effects requires accurate information of deep basin, this study aims to explore site characteristics by microtremor observations and to investigate amplifications by site response analysis. Array microtremor techniques employed in this work were the Spatial Autocorrelation (SPAC) method and the Centerless Circular Array (CCA) method. Longer detectable wavelengths were obtained by the CCA method. Shear wave velocity from the derived dispersion curves of 50 study sites exhibit very low value and the inferred depth of bedrock varied from 400 to 800 m. Transfer functions calculated by equivalent linear analysis showed amplifications in long period from 0.8 to 5 seconds and they are comparable to the spectral accelerations recorded from remote earthquakes.

1 INTRODUCTION

Local site conditions can considerably influence the characteristics of ground shaking from earthquakes, such as amplitude, period and duration. Lessons from devastating earthquakes have shown that ground motion intensity can be amplified, long period vibrations become dominant, and duration of shaking can be lengthened due to a seismic interaction of soft shallow soil layers with deep basin structure below at the site. The amplification characteristics of long period ground motion are substantially influenced by dynamic properties of soil at deeper level. The city of Bangkok, Thailand, and surrounding region is situated on a large plain underlain by thick alluvial and deltaic sediments of the Chaophraya Basin known as Bangkok clay. The basin covers approximately 10,000 square kilometres area with a population of over ten million. 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 hundred meters, but there is no sufficient data available at present. Recent studies indicated that the average shear wave velocity of the upper layers was very low (Poovarodom and Plalinyot, 2013). 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 from the Sumatra subduction zone. Two recent examples of observed site effects from distant earthquake are; (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 and the other in Surin, located at the same distance but founded on stiff soil. Spectral acceleration amplifications in Bangkok are remarkable especially for period range of 0.6 to 2.5 seconds, and the second amplification of about 4 to 6 seconds. The problem of long period amplifications in Bangkok is focused in this study. Site investigations for velocity structures were conducted by microtremor observations to estimate phase velocities and shear wave velocities profiles. The microtremor techniques were the Spatial Autocorrelation (SPAC) method (Aki, 1957) and the Centerless Circular Array (CCA) method (Cho et. al., 2006a, b). The benefit of using the CCA method was discussed from the results of the observation sites. Total 50 sites were explored for shear wave velocity profile down to about 1 km. Amplification characteristics were examined by computing site transfer function from shear wave velocity model by using the one-dimension equivalent linear method.

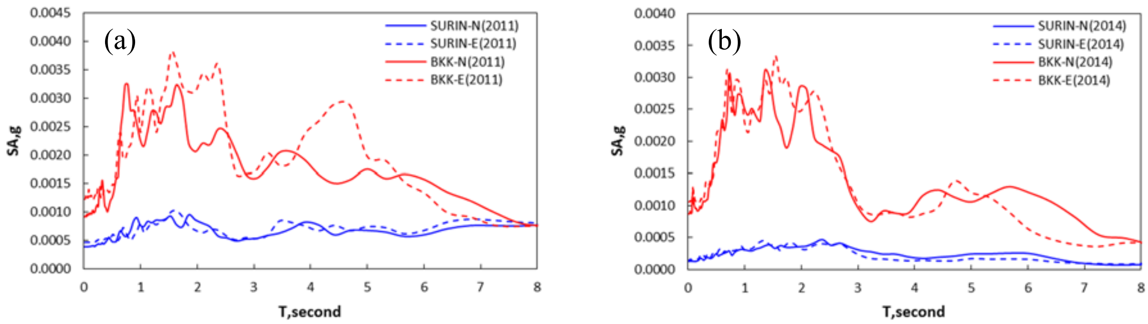

Figure 1. Spectral Acceleration at Bangkok (soft soil) and Surin station (stiff soil) (a) 2011 event, (b) 2014 event.

2 TECHNIQUES OF MICROTREMOR OBSERVATION

In this study, the microtremor measurements were conducted for extensive surveys in the studied area to provide site characteristics useful for examination of ground motion amplifications. Two techniques of extracting phase velocities from microtremors employed were the Spatial Autocorrelation method (SPAC) and the Centerless Circular Array Method (CCA). The observed phase velocities were subsequently inversed to shear wave velocity profile of subsoils.

2.1 Spatial Autocorrelation Method (SPAC)

This technique was proposed by Aki (1957) based on the relationship between the temporal and spatial spectra of waves to obtain phase velocity dispersion curve. The basis of SPAC method is to simultaneously record the vertical component of microtremors for several positions 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 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 interstation distance $r, \rho(\omega, r)$. By assuming that, the wave energy propagates with only one velocity at each frequency, ω, it can be shown that the spatial autocorrelation coefficient for a circular array is given by equation (1) (Aki 1957, Okada 2003).

$$\rho(\omega,r) = \frac{Re\left[E\left[C_{A,B}(\omega)\right]\right]}{\sqrt{E\left[C_{A,A}(\omega)\right]E\left[C_{B,B}(\omega)\right]}} = J_0(k(\omega)r) = J_0\left(\frac{\omega r}{c(\omega)}\right) \quad (1)$$

Where $E[.]$ Denotes an ensemble average over time, $C_{A,B}(\omega)$ is cross spectra of vertical records at two stations, A and B, J_0 is the Bessel function of the first kind with the zero-th order, *k(ω)* and *c(ω)* are the wavenumber and (dispersive) phase velocity, respectively, at frequency ω for the Rayleigh waves with the fundamental mode. The phase velocity can then be determined by fitting the observed SPAC coefficients at various r for each frequency with $J_0\left(\frac{\omega r}{c(\omega)}\right)$.

2.2 Centerless Circular Array Method (CCA)

This technique was developed by Cho et al (2006a, b) 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;

$$Z_0(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)d\theta \quad (2)$$

$$Z_1(t,r) = \int_{-\pi}^{\pi} z(t,r,\theta)\exp(i\theta)d\theta \quad (3)$$

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;

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

Where J_1 is the Bessel function of the first kind with the first order. The wavenumber, and phase velocity, 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 general practice which noise is contained, equation (4), for the case of the fundamental mode dominating, can be shown as;

$$\frac{G_0(r,r;\omega)}{G_1(r,r;\omega)} = \frac{J_0^2(rk(\omega))+\varepsilon(\omega)/N}{J_1^2(rk(\omega))+\varepsilon(\omega)/N} \tag{5}$$

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;

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

$$A = -\rho^2, B = \frac{\rho^2}{coh^2} - 2\rho^2 - \frac{1}{N}, C = \rho^2\left(\frac{1}{coh^2} - 1\right)$$

ρ is defined in equation (1), $coh^2 = \frac{|G_0(0,r;\omega)|^2}{G_0(r,r;\omega)G_0(0,0;\omega)}$, and N is the number of sensors along the circumference.

2.3 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 best-fit shear wave velocity–depth profile were determined from the inversion analysis, in which this study applied the technique developed by Yokoi (2005) which employs the combination of Down Hill Simplex Method with Very Fast Simulated Annealing.

3 FIELD OBSERVATIONS AND DATA ANALYSIS

3.1 Area of Study

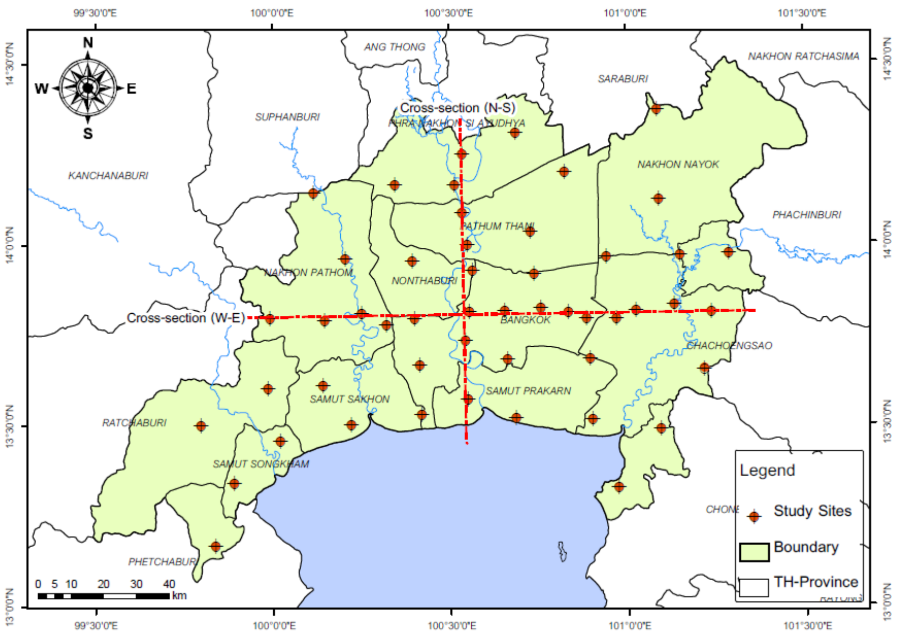

Figure 2. Area of study in the Greater Bangkok

The investigated area is located within latitudes 13°2'46" N to 14°25'8" N and longitudes 99°39'18" E to 101°21'35" E, covering Bangkok and the vicinity provinces. The area lies on a large alluvial plain of delta area where four main rivers empty into the Gulf of Thailand in the south. Figure 2 shows the investigated area where 50 observation sites are distributed almost evenly inside. Variations of the shear wave velocity profiles will be presented along two straight lines as cross sections of the study area.

3.2 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 synchronization between each unit was enabled by GPS clock with a resolution of 1 /100 seconds. Before conducting array microtremor observation, a test was performed to check the coherency of amplitudes and phase differences among the sensors by placing them closely next to each other and comparing their signals. The applicable range of frequency for the equipment was identified as from 0.3 to 20 Hz. The arrangement of sensors was an equilateral triangular array with one unit placed at the center of a circle and the other three on its perimeter. Four different sized array arrangements were set at each site with radius (r) of 5, 30, 100 and 250 m.

3.3 Data Interpretation

The following discussion analyses representative results for phase velocities 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 and CCA analysis are shown in Figure 3 and 4, respectively. For SPAC method, Figure 3(a) shows an arithmetic mean of the observed SPAC coefficients with the interstation distance of 250 m from three pairs of sensors and Figure 3(b) shows a plot of J_0. From these SPAC coefficients, the dispersive phase velocity at a particular frequency was obtained as the argument of the Bessel function of Equation (1). Lines connecting between the two figures represent one-to-one matching of the observed $\rho(\omega, r)$ with $J_0(x_i)$. The matched frequencies f_i from (a) and x_i from (b) are identified from the points having equal ordinate. Figure 3(c) shows phase velocities calculated from $c_i = 2\pi r f_i / x_i$. Finally, Figure 3(d) is an ensemble of phase velocities extracted from different arrays.

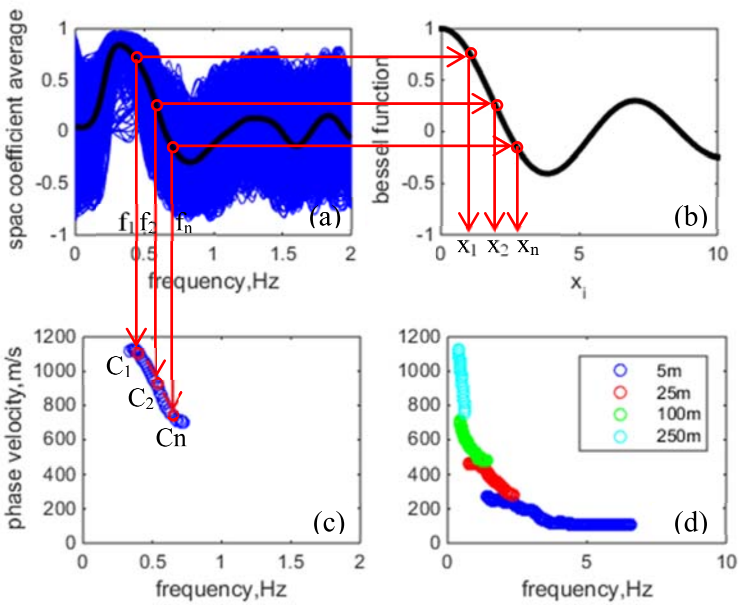

Figure 3. Example of SPAC analysis; (a) SPAC coefficients for 250-m array, (b) Bessel function J_0, (c) estimated dispersion curve for this array, and (d) final dispersion curve

Similarly for CCA, Figure 4(a) and (b) show the observed spectral ratio and the ratio of Bessel function as in Equation (5), 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 4(c). Their ensemble for different arrays are plotted in Figure 4(d). Figure 5 shows comparison of computed wavelength from both techniques. It can be clearly noted that 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 exhibit similar findings so that this study presents the following results as those obtained from the CCA method.

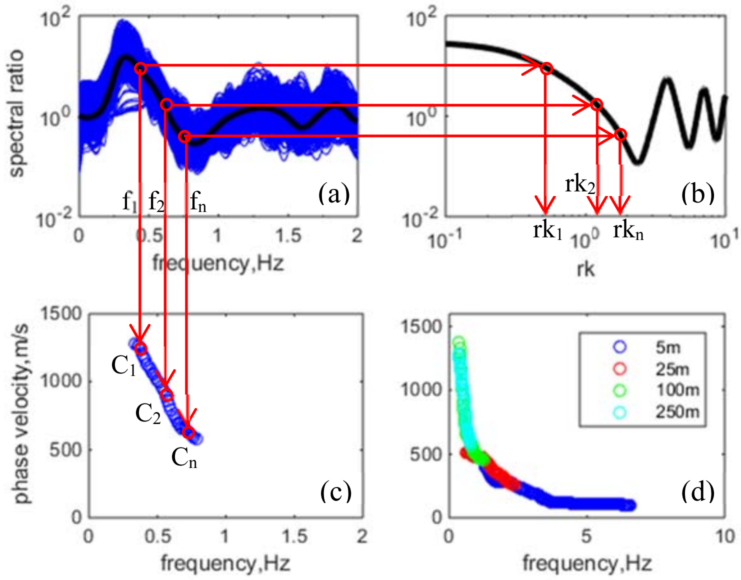

Figure 4. Example of CCA analysis; (a) spectral ratio for 250-m array, (b) ratio of Bessel function as in Equation (5), (c) estimated dispersion curve for this array, and (d) final dispersion curve

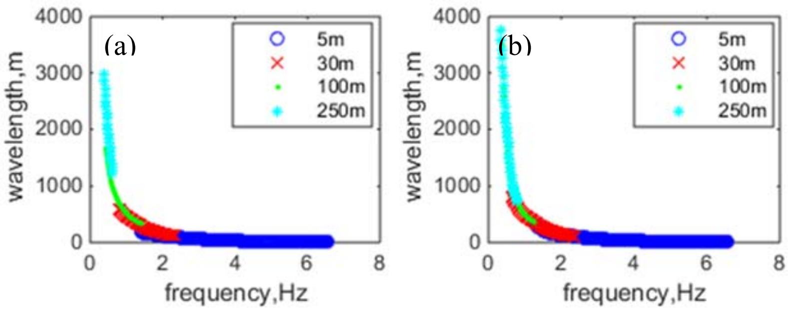

Figure 5. Computed wavelength (a) from the SPAC method, (b) from the CCA method.

4 RESULTS AND DISCUSSIONS

4.1 Phase Velocity and Shear Wave Velocity

The results of phase velocities of 50 observation sites are plotted versus periods in Figure 6(a). It can be noted that large variations exist, indicating remarkable differences of site characteristics inside the study area. Since waves propagating with short period possess short wavelength and they travel near surface, dispersion curves of high phase velocity at short period represent the waves travel with high velocity (in stiff media) near the surface. Then the sites having steep dispersion curves, on the left hand side part, lie on much stiffer soil. Those sites are located near the boundary of the study area. While the majority of the sites are softer with moderate slope of dispersion curves and located around the center of the basin. The consequent shear wave velocity profiles were calculated and they are presented in Figure 6(b). Generally, shear wave velocities of the first 100 m deposits are less than 500 m/s. The velocities increase gradually along depth and the underneath layers of stiffer soil exhibit moderate shear wave velocity of about 500 to 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 level of such high contrast in velocity varies from 400 m to 800 m inferring the depth of bedrock for each site.

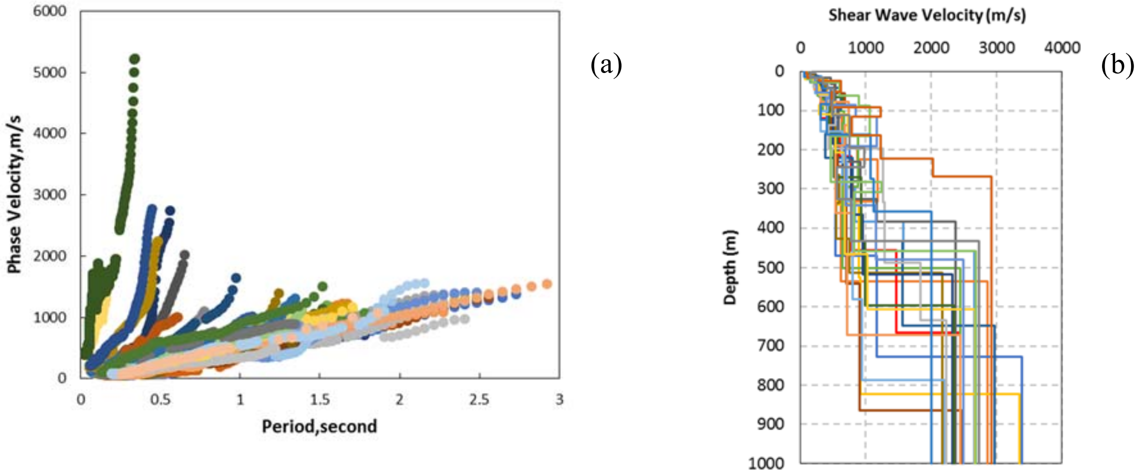

Figure 6. Results of 50 sites; (a) Phase velocity dispersion curves, (b) Shear wave velocity profiles.

4.2 Shear Wave Velocity Profile along Cross Section

Variations of shear wave velocity are illustrated as 2D cross-sectional profiles in Figure 7 and 8 for north-to-south (8 sites and 80 km long) and west-to-east directions (14 sites and 140 km long), respectively. The ordinates in the upper graphs are the estimated depth of bed rock inferred from the level with clear contrasts of shear wave velocity in which the velocity changes abruptly to be about 2000 m/s or more. The shear wave velocity profiles are plotted along with their position in the cross sections. The estimated depth of bedrock varies from 400 to 800 meters. The boundary of the basin possesses shallower depth of bedrock comparing with the central area of Bangkok.

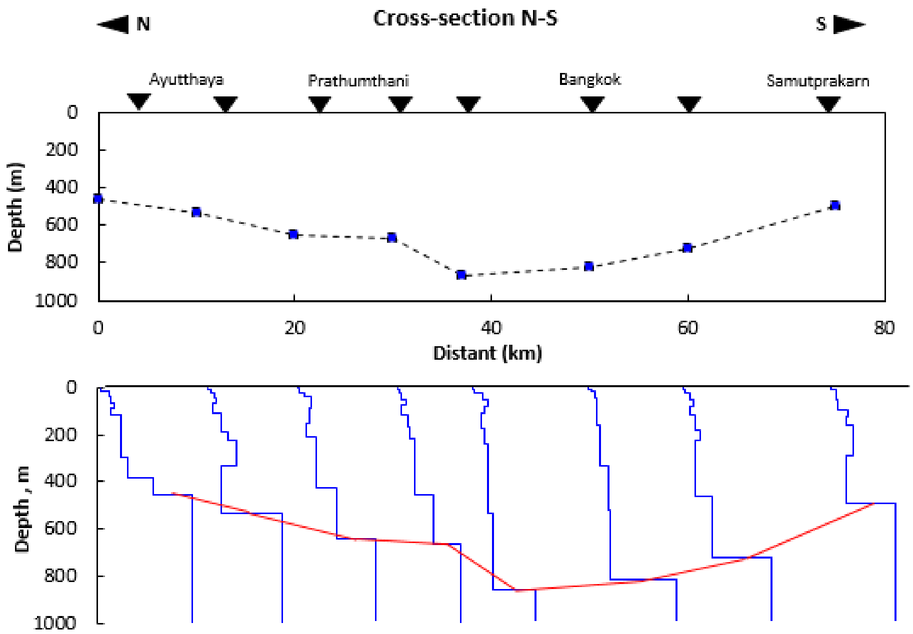

Figure 7. Variations of depth of bedrock and shear wave velocity profile along N-S cross section.

4.3 Transfer Function

From the computed shear wave velocity profiles, soil layers of each site were modelled for a purpose of investigations of amplification characteristics by site response analysis. Transfer functions of vertical propagation of wave were analyzed by equivalent linear analysis using SHAKE program (Schnabel 1972). Damping ratio was assumed to be 5% of the critical value, which was estimated by average damping ratio of soil layers under a moderate earthquake of Bangkok. The results can be classified into three groups based on the estimated depth of bedrock, D, as; (1) D < 500 m, (2) 500 m < D < 650 m, and (3) D > 650 m. Transfer functions of group (1) to (3) are presented in Figure 9(a) to (c). For sites having relatively shallow bedrock in group (1) strong amplification at period about 1 second are dominant. The second amplification periods are about 2 or 3 seconds. In group (2), the maximum amplifications are lessen in period of 1 second, but the period ranges of amplification are broaden. The periods of the second amplification are about 3 seconds. For sites with deep sediments in group (3), since the level of high contrast shear wave velocity is very deep so that the maximum amplifications are further decreased. The period ranges of amplifications are from 1 to 5 seconds. The shape of the transfer function is comparable to spectral accelerations recorded from remote earthquake which was shown before in Figure 1. The locations of these sites are in central area of Bangkok where a number of high rise buildings have experienced long period vibrations from earthquake occasionally. The long period amplifications in this area indicate a potential risk from remote earthquake which can resonate with tall buildings having natural period in this range.

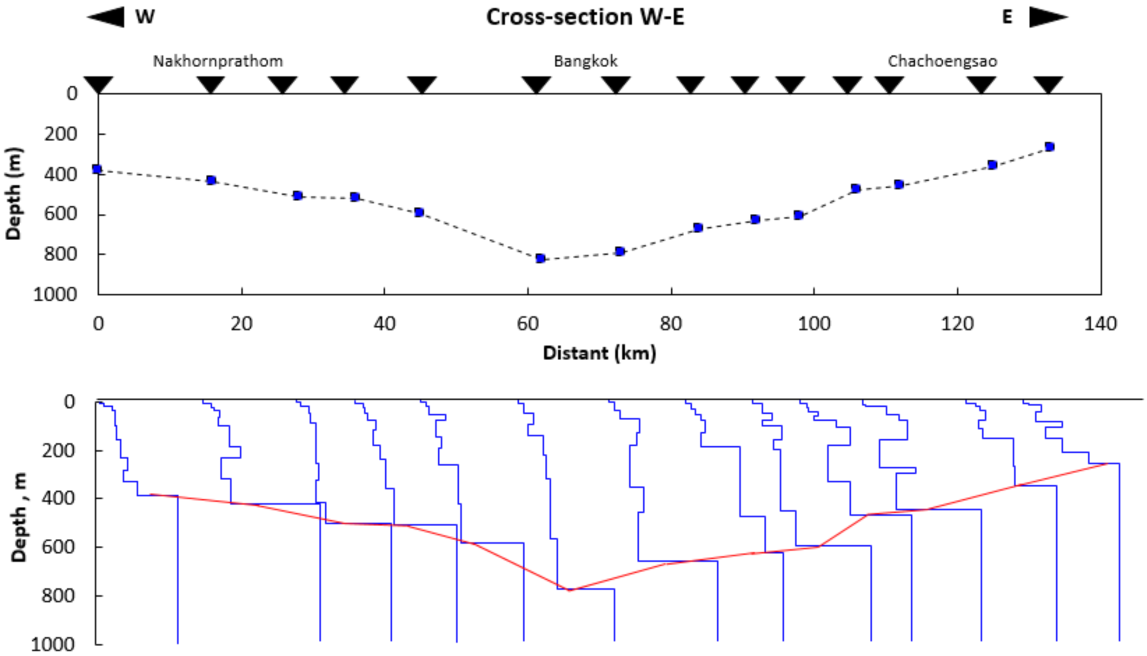

Figure 8. Variations of depth of bedrock and shear wave velocity profile along W-E cross section.

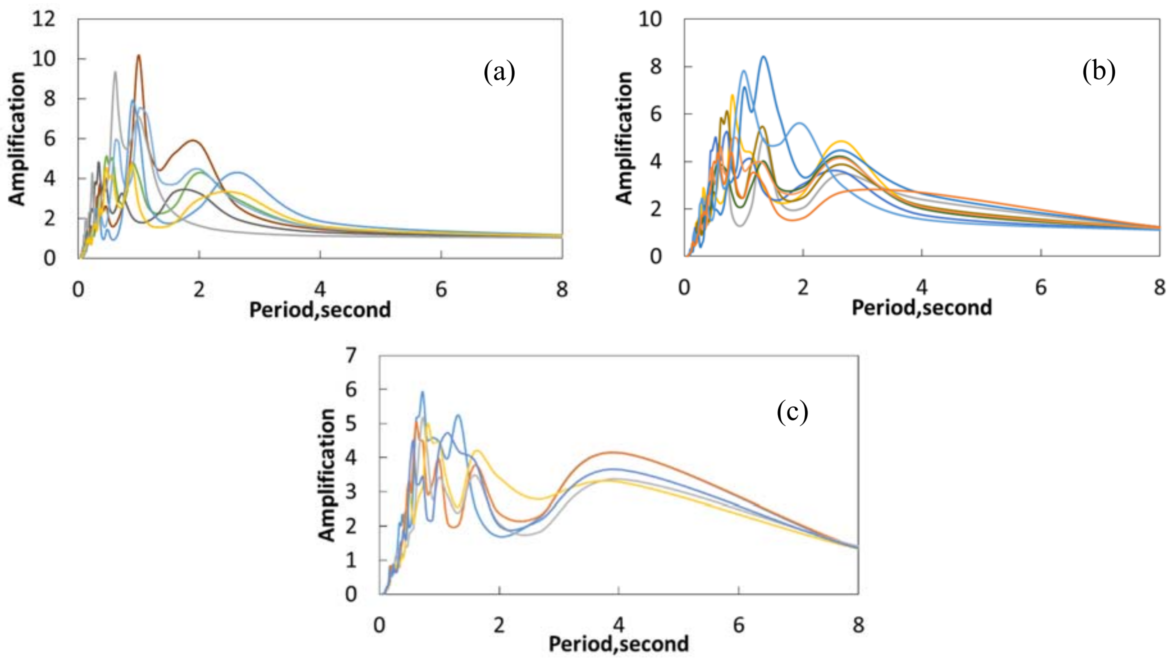

Figure 9. Transfer functions (a) group 1, (b) group 2, and (c) group 3.

5 CONCLUDING REMARKS

This paper presents a work on seismic site effects of deep basin in the Greater Bangkok focusing on long period amplifications. The study conducted site investigation by microtremor observation techniques and site response analysis by one-dimension equivalent linear method. Some key concluding remarks can be drawn as follows;

- Two microtermor techniques SPAC and CCA method were investigated for their efficiency in exploration of deep soil structure. The results confirmed that the CCA method could provide longer detectable wavelength and lower frequency range than the SPAC method. This exploration demonstrates an applicability of microtremor technique with long period component for deep sedimentary layers as Bangkok basin.
- Shear wave velocity profiles of 50 sites were explored down to bedrock level. Cross sectional profiles along north to south and west to east of the study area were presented to depict the shape of the basin underneath the sediments. The estimated depth of bedrock varies from 400 to 800 meters. The boundary of the basin possesses shallower depth of bedrock comparing with the central area of the basin.
- Transfer functions obtained from site response analysis exhibit amplifications in wide range of periods. High amplifications were observed because of very low shear wave velocity at the sedimentary layers and high contrast of shear wave velocity at bedrock level.
- The long period effects were clearly indicated for the period up to 5 seconds especially in the sites having depth of bedrock over 650 m. The calculated transfer functions were comparable to the spectral accelerations recorded from remote earthquakes. This finding could explain resonant vibration of tall buildings having natural periods in this amplification range and emphasis potential risk from remote earthquakes affecting Bangkok.

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