17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

ESTIMATION OF SHEAR WAVE VELOCITY PROFILES BASED ON EXTENSIVE MICROTREMOR SURVEYS IN BANGKOK DEEP BASIN

A. Jirasakjamroonsri(1), N. Poovarodom(2)

(1) Postdoctoral Fellow, Department of Civil Engineering, Thammasat University, Thailand, amorntep_aj@hotmail.com
(2) Associate Professor, Department of Civil Engineering, Thammasat University, Thailand, pnakhorn@engr.tu.ac.th

Abstract

Shear wave velocity (V_S) structure beneath the ground surface is one of the most important parameters for seismic site response analysis. V_S profiles are used to construct soil models for analyzing ground response at the site. At present, several noninvasive techniques have been developed as alternative tools for field investigation. In these techniques, the dispersive characteristics of surface waves are first computed, then the inversion analysis is carried out to obtain the V_S profile. In some cases, there are some limitations of the testing technique or the unfavorable field conditions. Then the results could be obtained only from the shallow structure. However, deep V_S profiles are essential for estimating ground response at long period. Therefore, it is beneficial to investigate the relationships among average V_S at different depth (V_{SD}) in order to propose the extrapolating equations for deep V_S. Besides, the inversion analysis requires an initial range of V_S values as one of the input parameters. In this technique, efficient analysis can be performed when using the proper range of initial input parameters. Thus, a simple estimation of V_S profiles is useful. This paper investigates and proposes simple techniques to estimate the V_S in two aspects; first, the extrapolation equations of the average V_S at the deeper depth from shallow V_S (e.g. V_{S30}) is proposed based on the correlation among V_{SD}. Second, a simple scheme to construct V_S profile is presented based on the phase velocity dispersion curve without an inversion analysis. The proposed estimations in this paper were derived from V_S profile of 170 sites obtained from array microtremor observation in Bangkok basin, central Thailand with different site conditions over an area of approximately about 16,000 km^2. From a number of the observed sites, the relations among the V_{SD} and V_{S30} were examined. The regression analysis revealed high correlations and almost linear relations among them, suggesting that V_S at deep strata could be estimated from the shallow V_S. Moreover, a simple scheme to estimate the V_S profile using only the phase velocity at a specific wavelength is proposed. The predictions V_S profile by this technique shows satisfactory results with those obtained from an inversion analysis, especially in thick and soft soil sites of the deep basin.

Keywords: Site effects; Site Characteristics; Shear wave velocity; Microtremor; Bangkok basin

1. Introduction

In geotechnical earthquake engineering, shear wave velocity (V_S) of soil layers is one of the most important parameters for investigation of ground amplification due to seismic waves propagation. By geophysics methods, it can be practically derived from an inversion analysis of phase velocity of the Rayleigh wave. To acquire such characteristics, due to the unfavorable field conditions or testing technique limitations, only the shallow V_S can be obtained in some situations. However, deep information is essential for computing ground responses at long period. Therefore, an accurate estimation technique for deep V_S profile from shallow V_S is useful in this problem. In addition, to calculate V_S profile from inversion analysis, an initial trial of V_S should be appropriately assumed. The analysis can be performed efficiently when using the initial range of the input parameters, which is close to the final result. The objective of this paper aims to present simple techniques to estimate V_S in the aspects mentioned above. First, equations for extrapolation of the deeper profile from shallow V_S (e.g. V_{S30}) are proposed based on the correlation among V_{SD}. Second, a simple scheme to construct V_S profile is presented, using specific wavelengths from the phase velocity dispersions curve. The V_S profiles for investigation in this study were obtained by an extensive of array microtremor surveys in Bangkok and the vicinity area. The Spatial Autocorrelation (SPAC) method [1] and the Centerless Circular Array (CCA) method [2] were employed in 170 sites with different site conditions to estimate the dispersive characteristics of phase velocity. At each site, the technique of an inversion analysis was applied to inverse the dispersion curve to the V_S profile down to a depth of 100 m.

2. Area of study

The study area is located in the Lower Central plain of Thailand, within latitudes 13.0285° N to 14.3610° N and longitudes 99.5733° E to 101.4333° E, covering 14 provinces. Fig. 1 shows the investigated area and location of the observation sites. The size of this area is approximately about 17,500 square-kilometers with an approximate distance of 130 and 180 kilometers in North-South and East-West directions respectively.

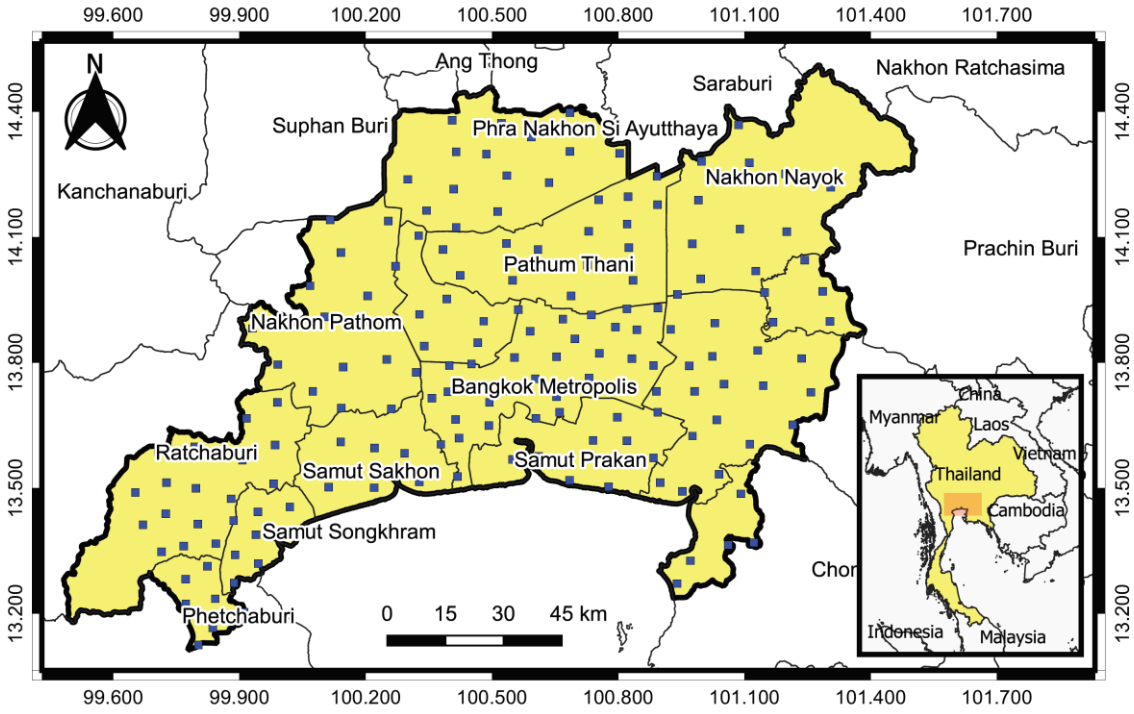

Fig. 1 – Area of study

3. Methodology and field observation

In this study, the array microtremor measurements were conducted for extensive surveys in the studied area. The Spatial Autocorrelation method (SPAC) [1] and the Centerless Circular Array (CCA) [2] were employed in this study. The observed phase velocities were inversed to shear wave velocity profile of subsoils by using an inversion analysis [3,4].

3.1 Spatial Autocorrelation method (SPAC)

This method was proposed by Aki [1] based on the relationship between the temporal and spatial spectra of waves to obtain the phase velocity dispersion curve. The details of this techniques were presented comprehensively by Okada [5]. 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 Eq. (1).

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

Where $E[\bullet]$ 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 order, $k(\omega)$ and $c(\omega)$ are the wavenumber and (dispersive) phase velocity, respectively, at frequency ω for the Rayleigh waves with the fundamental mode. Finally, the phase velocity can be computed by Eq. (2).

$$c_i=\frac{2\pi f_i r}{X_i} \tag{2}$$

Where c_i, f_i, r_i and X_i are (dispersive) phase velocity, frequency, radius, and abscissa of a plot of the Bessel function, which correlated to the SPAC coefficient in Fig. 2(a) and Fig. 2(b).

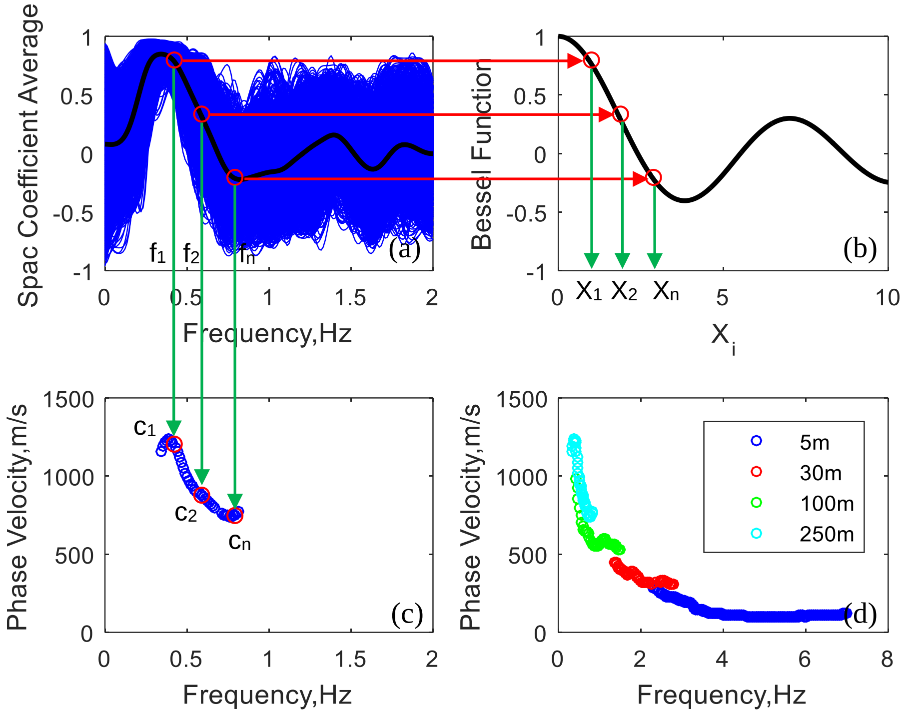

Fig. 2 – Procedures of SPAC method; (a) Average SPAC coefficient from the experiment, (b) Bessel function, (c) Phase velocity for array 250 m., and (d) Total phase velocity of the sample site

3.2 Centerless Circular Array (CCA)

The technique of Centerless Circular Array (CCA) method was proposed by Cho et al. in 2006 [2]. The basis of this method is used the record of microtremor in the vertical component. At least three velocity sensors were placed around the circular array and one at the center of the circle. This technique assumes that the Rayleigh waves propagate as plane waves and arrive from different directions and intensity. Because Rayleigh waves are uncorrelated in general cases, they can be regarded as a random field which is stationary in both time and space. Noise from the record, which is the non-propagating wave is assumed for simplicity as stationary and uncorrelated to the microtremor signals. The power spectral density ratios from all sensors around the perimeter are computed from vertical recorded data to evaluate the correlation with the theoretical power spectral density ratio and then calculate phase velocity characteristic. The relation between the spectral ratio from experiment and theoretical can be expressed as Eq. (3).

$$\frac{G_{Z0Z0}(r,r,\omega)}{G_{Z1Z1}(r,r,\omega)} = \frac{J_0^2\left(rk^R(\omega)\right)+\varepsilon^V(\omega)/N}{J_1^2\left(rk^R(\omega)\right)+\varepsilon^V(\omega)/N} \tag{3}$$

From Eq. (3), the spectral ratio on the left-hand side is obtained from the experiment and radius, r is known parameter. N is the number of sensors placed around the perimeter. $\varepsilon^V(\omega)$ is the noise to signal ratio, representing the power of the incoherent noise to the power of the coherent signal. Assume that the fundamental mode is dominant, ε can be estimated by Eq. (4).

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

Where $A=-\rho^2, B=\dfrac{\rho^2}{coh^2}-2\rho^2-\dfrac{1}{N}, C=\rho^2\left(\dfrac{1}{coh^2}-1\right)$, ρ defined in Eq. (1), $coh^2=\dfrac{\left|G_0(0,r;\omega)\right|^2}{G_0(r,r;\omega)G_0(0,0;\omega)}$. Then, wavenumber, $k^R(\omega)$ for each frequency (ω) can be computed from the relationship between the experiment and the theoretical spectral ratio in Fig. 3(a) and Fig. 3(b). Phase velocity, $C^R(\omega)$ can be computed by Eq. (5).

$$C^R(\omega)=\omega/k^R(\omega) \tag{5}$$

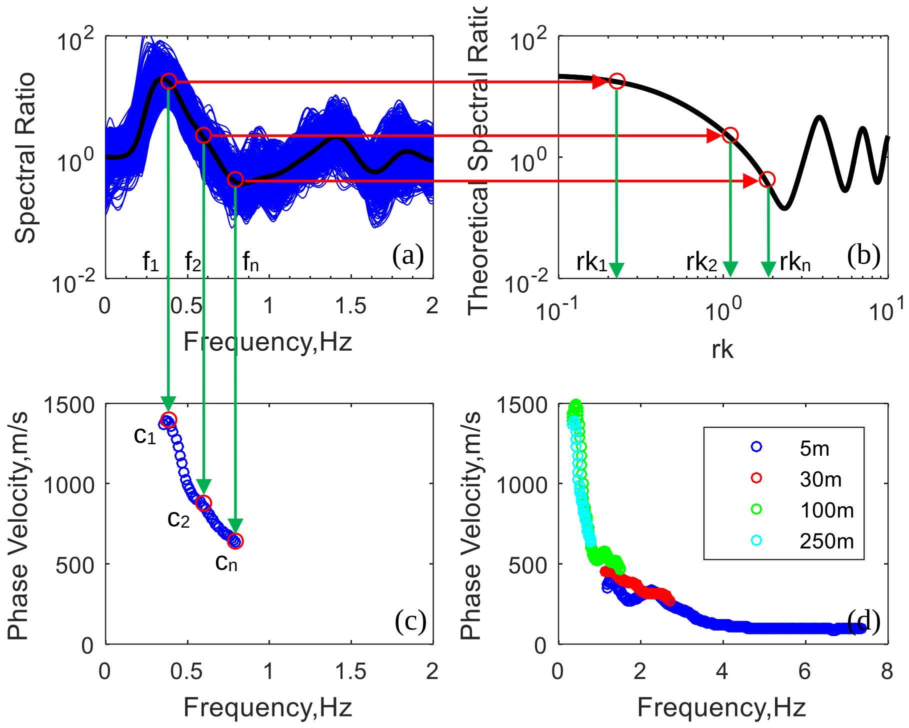

Fig. 3 – Procedures of CCA method; (a) Average spectral ratio from the experiment, (b) Theoretical spectral ratio, (c) Phase velocity for array 250 m., and (d) Total phase velocity of the sample site

3.3 Inversion analysis

The shear wave velocity profile from the surface to basement rock level can be derived by an inversion analysis. The dispersion relation of phase velocity and frequency from field observations are compared with those derived theoretically from a horizontally layered earth model by iteration procedure to provide the best-fit shear wave velocity–depth profile. However, there are always be several possible solutions from the inversion analysis, indicating the problem of non-uniqueness solutions. This study carefully selects the solutions with the minimum level of misfits and employs two algorithms for inversion analysis as; the combination of Down Hill Simplex Method with Very Fast Simulated Annealing [3] and the neighbourhood algorithm [4].

3.4 Field observation

Field observations were performed using a measuring system consisted of a data acquisition instrument with a 32-bit A/D converter and four-velocity sensors of moving coil type with a 10-second natural period. The applicable frequency response range is 0.1–70 Hz. The arrangement of sensors for the SPAC and CCA observation was an equilateral triangular array with one sensor placed at the center of a circle and the other three on its perimeter. The size of array arrangements was set with radius (*r*) in a range of 5 to 250 m. Each set measured simultaneously with the time synchronization using a clock from the GPS with a resolution of 1/100 seconds. In addition, pairs of the peripheral stations with the inter-station distance $\left(\sqrt{3}r\right)$ was also included in the analysis of SPAC method. For each observation, data were collected for 40 minutes with a sampling frequency of 100 Hz.

4. Results and discussions

4.1 Relationship among V_{SD} and V_{S30}

In this section, the estimation of deeper velocity structures is presented. In the past, some researches proposed the equations to estimate V_{S30} from shallower V_S profiles in case of unfavorable field conditions [6]. On the other hand, extrapolation of V_{S30} for deeper structures is beneficial for better understanding of site effects caused by deep sediments. Thus, this study was conducted to examine if V_{S30} can be used to extrapolate for deeper velocity structures. The generalized relations between shear wave velocity at different depth (V_{SD}) and V_{S30} can be shown in Eq. (6).

$$V_{SD} = \alpha\left(V_{S30}\right)^{\beta} \tag{6}$$

Eq. (6) can be re-written as a linear equation to determine the coefficients α and β in the regression analysis as shown in Eq. (7).

$$y = a + \beta x \tag{7}$$

In which $y = \log\left(V_{SD}\right), a = \log\left(\alpha\right)$ and $x = \log\left(V_{S30}\right)$. The plots of Eq. (7) can provide the interception a at $x = 0$ and slope β of the straight line by minimizing the standard error of estimate between the measured and the predicted values. Fig. 4 shows the relationships between V_{S30} and V_{SD} from the observations as markers and the regression equations as lines in Fig. 4. The results of the regression analysis are shown in Table 1.

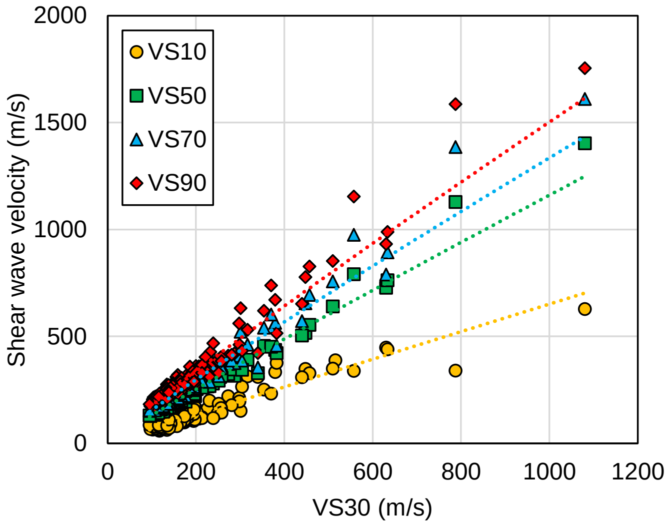

Fig. 4 – Relationships between V_{S30} and V_{S50}, V_{S70}, and V_{S90}

Table 1 – Results of regression analysis for V_{S30} with V_{S10}, V_{S50}, V_{S70}, and V_{S90}

V_{SD}	α	β	R^2
V_{S10}	0.7166	0.9861	0.8932
V_{S50}	1.6805	0.9464	0.9802
V_{S70}	2.1216	0.9329	0.9586
V_{S90}	2.4555	0.9289	0.9425

The results show that the exponent β is almost unity in all cases, or the relationship between V_{S30} and V_{SD} is nearly in linear proportion. In addition, highly correlated relationships among V_{S30} and V_{SD} are observed from large R^2. The results suggest that V_{S30} could be used to estimate the V_S at deeper strata for thick and soft sedimentary sites.

4.2 Estimation of shear wave velocity from the phase velocity

Generally, V_S profile can be obtained by an inversion analysis. In this process, a set of the initial range of soil model with the primary wave velocity (V_P), V_S, density and thickness for each layer must be assumed to control the final solutions. In this section, a simple and rapid technique to estimate V_S profile directly from the phase velocity is proposed. In a past study, Konno [7] proposed a simple approach to estimate V_{S30} without an inversion analysis which approximately equal to the phase velocity at wavelengths of 35 to 40 m. In this section, phase velocity at some specific wavelengths, C_λ , from the dispersion curves of 170 sites were examined for their correlations with V_{S10} to V_{S90}. From the results, the most correlated C_λ with V_{SD} were searched in each dispersion curve and the results show in Table 2

Table 2 – Correlation between V_{SD} and C_λ

V_{SD}	C_λ	R^2
V_{S10}	C_{20}	0.9606
V_{S30}	C_{40}	0.9467
V_{S50}	C_{60}	0.9299
V_{S70}	C_{80}	0.9444
V_{S90}	C_{100}	0.9534

From Table 2, the coefficients of R^2 are considerably high in all cases. This result suggests that information of C_λ could be practically used to estimate V_{SD} with satisfactory accuracy. From these correlations, shear wave velocity at a depth of 10 m (V_{10}) to 90 m (V_{90}) can be obtained by using the Eq. (8) to Eq. (12).

$$V_{10} = C_{20} \tag{8}$$

$$V_{30} = 20\Big/\left(\frac{30}{C_{40}} - \frac{10}{V_{10}}\right) \tag{9}$$

$$V_{50} = 20\Big/\left(\frac{50}{C_{60}} - \frac{10}{V_{10}} - \frac{20}{V_{30}}\right) \tag{10}$$

$$V_{70} = 20\Big/\left(\frac{70}{C_{80}} - \frac{10}{V_{10}} - \frac{20}{V_{30}} - \frac{20}{V_{50}}\right) \tag{11}$$

$$V_{90} = 20 \bigg/ \left(\frac{90}{C_{100}} - \frac{10}{V_{10}} - \frac{20}{V_{30}} - \frac{20}{V_{50}} - \frac{20}{V_{70}} \right) \tag{12}$$

Fig. 5 shows the comparison between V_S profile from the estimation method and inversion analysis for example sites in three different groups of NEHRP [8] soil classification; (a) soil class E, (b) soil class D, and (c) soil class C. The results show that the proposed method is applicable to these ranges of soil types.

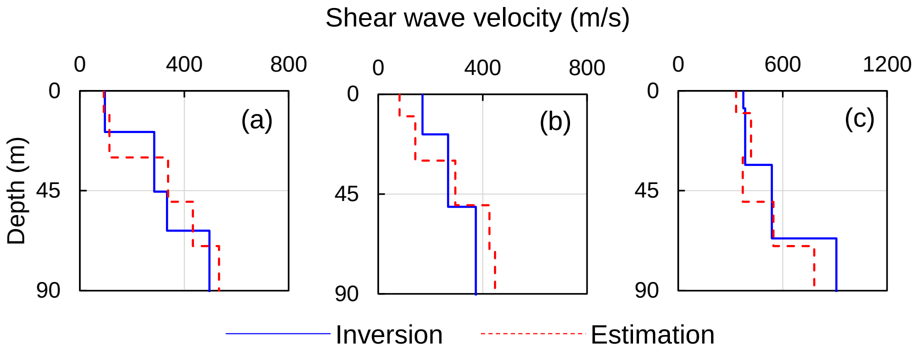

Fig. 5 – Comparison of V_S profile from the estimation method and inversion analysis

5. Conclusions

In this study, simple schemes useful for estimation of shear wave velocity are presented for two applications; the extrapolation equations of the average V_S at the deeper depth from shallow V_S and a simple scheme to construct V_S profile from the phase velocity dispersion curve without an inversion analysis. The database of V_S profiles to derive the proposed schemes was from extensive study of site characteristics of sediments in Bangkok and the vicinity area using microtremor observations. Array microtremor techniques, SPAC and CCA method, were used to estimate the phase velocity dispersion curve. Then, an inversion analysis was applied to estimate the V_S profiles. From the regression analysis, highly correlated relationships among V_{S30} and V_{SD} were identified, suggesting that the V_{S30} can be used to extrapolate the deeper velocity structure in thick and soft sedimentary sites. Finally, a simple technique for estimation of V_S profile by using the phase velocity at specific wavelengths was presented. The results revealed that the estimated V_S profiles from different soil types obtained from the proposed technique were conformed to those obtained from the inversion analysis. Moreover, the technique can provide a quick estimation of V_S profile at the site before the detailed inversion analysis.

6. Acknowledgements

This study is supported by the Thammasat University scholarship for a Ph.D. student and the Thailand Research Fund, research number RDG5630026. The authors also express their appreciations to Dr. Bhakapong Bhadrakom, Mr. Nuttaphon Magteppong, Mr. Akkarit Nantayotsakul, Mr. Narakorn Boontem, and Mr. Weera Choopthong for their assistance in field works.

7. References

[1] Aki K (1957): Space and Time Spectra of Stationary Stochastic Waves, with Special Reference to Microtremors. *Bulletin of the Earthquake Research Institute*, **22**,415–456.

[2] Cho I, Tada T, and Shinozaki Y (2006): Centerless Circular Array method: Inferring phase velocities of Rayleigh wave in broad wavelength range using microtremor records. *Journal of Geophysical Research* **111**, B09315.

[3] 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**.

[4] Wathelet M (2008): An improved neighborhood algorithm: Parameter conditions and dynamic scaling. *Geophysical Research Letters*, **35**, L09301, DOI:10.1029/2008GL033256.

[5] Okada H (2003): The Microtremor Survey Method (translated by Koya Suto). *Geophysical Monograph Series*, **12**, Society of Exploration Geophysicists.

[6] Sun C (2014): Determination of mean shear wave velocity to 30 m depth for site classification using shallow depth shear wave velocity profile in Korea. *Soil Dynamics and Earthquake Engineering*, **73**, 17-28.

[7] Konno K, Suzuki T, Kamata Y, and Nagao T (2007): Estimation of average S-wave velocity of ground using microtremors at strong-motion sites in Yokohama. *Journal of Japan Society of Civil Engineering*, **63**, 639–654 (in Japanese with English abstract).

[8] Building Seismic Safety Council (1995): 1994 Edition NEHRP Recommended Provisions for Seismic Regulations for New Buildings. FEMA 222A/223A, Vol. 1 (Provisions) and Vol. 2 (Commentary), Developed for the Federal Emergency Management Agency. Washington, D.C.