Engineering Journal issn: 0125-8281

Article

Accounting of the Overburden Pressure on Analysis of Down-Hole Seismic Shear Wave Velocity

Sirichai Pethrung[1,a], Supot Teachavorasinskun[2,b,*], and Sitthiphat Eua-apiwatch[3,c]

1 Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Krungthep, Bangkok, Thailand
2 Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Bangkok, Thailand
3 Department of Civil Engineering, Faculty of Engineering, Burapha University, Chonburi, Thailand
E-mail: [a]sirichai.p@mail.rmutk.ac.th, [b,*]tsupot@chula.ac.th (Corresponding author), [c]sitthiphat@eng.buu.ac.th

Abstract. Shear wave velocities in soil reveal vital information to geotechnical engineers and their rates directly relate to effective stress conditions. Studies have extensively validated this dependency in theoretical models and laboratory tests but field measurements across different geographical regions require further exploration. This research analyzed seismic down-hole measurements across three Thai locations including Bangkok and the Maptaphut Industrial Estate and Chiang Mai province where the soils and geological landscapes differed substantially. The study evaluated four computational methods to calculate shear wave velocities including time-depth plot analysis and depth-time difference ratio and trigonometric distance-time difference approach and the virtual interface method that handles refraction effects at measurement depths. Traditional methods showed reduced capability to detect changes in overburden pressure because they produced sharp velocity fluctuations in shallow zones and at layer boundaries. The virtual interface method delivered superior velocity profile accuracy by integrating overburden pressure effects in the analysis. The site-specific logarithmic patterns between shear wave velocity and depth variations produced coefficients K and m that reflect soil composition and effective stress levels respectively. The studied regions exhibited contrasting parameters as Maptaphut sandy soils presented higher K values (100-160) and depth-dependent m values while Bangkok clay demonstrated K=12.52 and m=0.90. The trigonometric distance-time difference method stood out as an efficient computational method which minimized errors yet kept its applications straightforward.

Keywords: Shear wave velocity, overburden pressure, down-hole seismic test.

ENGINEERING JOURNAL Volume 29 Issue 6
Received 6 August 2024
Accepted 26 May 2025
Published 30 June 2025
Online at https://engj.org/
DOI:10.4186/ej.2025.29.6.1

DOI:10.4186/ej.2025.29.6.1

1. Introduction

The low strain amplitude shear modulus is a crucial parameter for conducting seismic response analysis of a subsoil profile. For a given soil, various laboratory procedures can be employed without much difficulty to determine this initial shear modulus and its related characteristics. These procedures and the importance of the initial shear modulus have been extensively discussed in the literature [1-8]. From these comprehensive studies, it has been established that the state of effective stress is one of the most significant factors influencing the values of the shear modulus. The relationship between effective stress and shear modulus exist in two basic mathematical expressions. The formulation of this theory exists as either stress dependence on mean effective stress or on individual stresses.

$$G_{ini} \propto (p^{'})^{m} \quad (1)$$

$$G_{ini} \propto \left(\sigma^{'}_{pd}\right)^{a}\left(\sigma^{'}_{pm}\right)^{b} \quad (2)$$

where

$p^{'}$ is the effective mean stress

$\sigma^{'}_{pd}$ is effective stresses in wave propagation direction

$\sigma^{'}_{pm}$ is effective stresses in particle motion directions

m, a, and b are material-specific constants.

The low-strain shear modulus measurement accuracy relies on testing high-quality undisturbed samples through state-of-the-art laboratory tests including resonant column testing, torsional shear testing and triaxial testing. Measuring it directly within the field environment proves to be complicated. Down-hole and cross-hole seismic measurements along with measurements of shear wave velocity represent indirect measurement methods because they provide the best representation of low-strain shear wave velocity [1, 2, 9,10]. The general relationship is:

$$G_{ini} = \rho v_s^2 \quad (3)$$

where

ρ is soil density

v_s is shear wave velocity.

The research presents particular importance because it analyzes varying analytical approaches in Thailand's regions which exhibit specific geological features. Field-based studies of shear wave velocity and overburden pressure effects remain relatively restricted throughout Southeast Asian regions because of their distinctive soil features. This research addresses important unknowns in how soils behave in real field settings which will help engineers who work in these areas.

The assessment of problematic soil strata through geophysical techniques warrants attention according to research conducted in areas containing collapsible soils throughout northeastern Thailand [11]. Research presented in this study provides a comprehensive evaluation of overburden pressure effects on shear wave velocity measurements through down-hole seismic testing whereas previous studies did not address this aspect. This study enhances existing knowledge about shear wave velocity response to overburden pressure variations across Thailand's varied geological domains.

The cross-hole seismic test stands as a highly reliable instrumental approach for measuring soil stratification and determining shear wave velocity. The cross-hole placement system allows test instruments to sense shear wave motions throughout the analyzed soil stratum leading to precise and dependable information. The setup comprised of Fig. 1 features separate source and receiver positions in different boreholes to measure shear wave travel times between these points. The exact measurement procedure serves as the foundation for soil property characterization and site geotechnical evaluation. The cross-hole test has high cost implications that can restrict its implementation in certain geotechnical projects.

A down-hole seismic test requires the installation of a cased borehole at the measurement site as shown in Fig. 2. The drilled borehole creates a stable testing area for instrument placement and conducting tests in a controlled space. A wooden plank requires placement at a pre-determined length from the borehole to generate shear waves. Striking the wooden plank utilizes a hammer attached to an accelerometer. The accelerometer precisely measures both strike-force and timing parameters so researchers can obtain accurate measurement data.

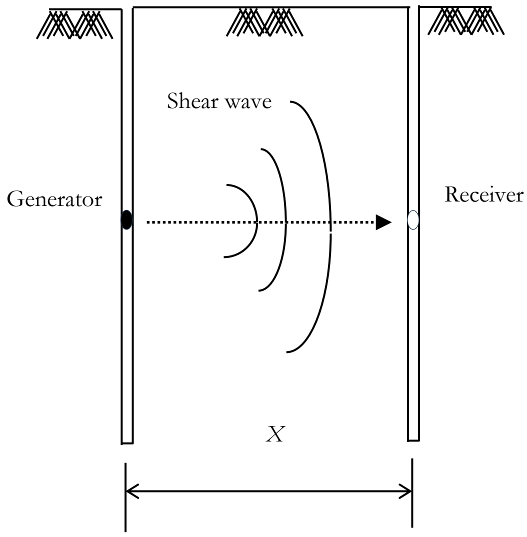
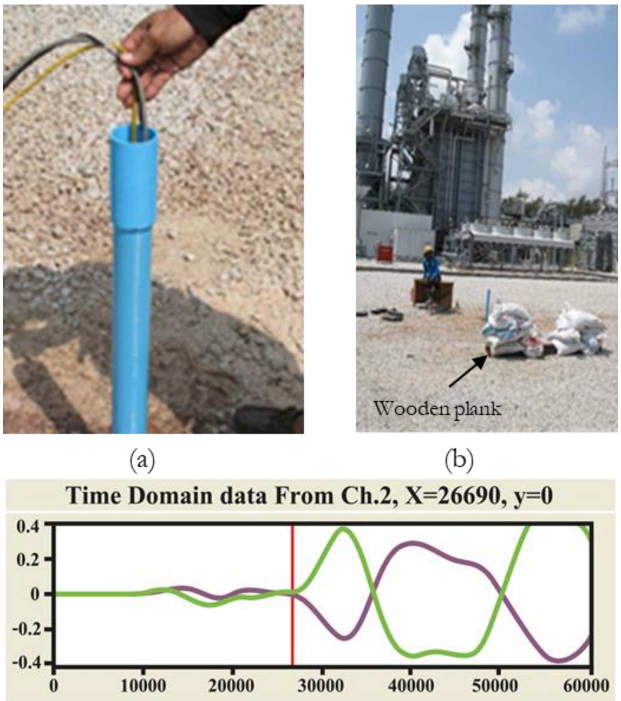


Fig. 1. General arrangement of the cross-hole seismic test showing the positions of generator, receiver, and shear wave propagation path.

The borehole depth measurement process requires two strikes to each wooden plank side at specific depths. A dual-hit mechanism proves vital by generating shear waves that move in different paths to distinguish actual shear wave data from background noise. The recorded time duration between when the wood plank produces waves starting from their origin point to when they reach the borehole sensors enables researchers to determine shear wave arrival times.



(c)

Fig. 2. Field implementation of down-hole seismic testing at the Maptaphut site: (a) insertion of receiver sensor, (b) wooden plank positioning and hammer setup, and (c) sample time-domain data record showing shear wave arrival detection. shear wave propagation through subsurface soil layers.

This well-established laboratory knowledge has shown slow progress in its transfer to field measurement applications. Scarce research exists to explain how different down-hole stress states influence seismic testing outcomes [8,9,12,13]. Sophisticated studies using seismic cone tests both in [9,14] failed to consider this essential factor. The present study evaluated down-hole seismic test data obtained from different sites across Thailand through multiple established computational procedures. The research aimed to assess whether shear wave velocity detected through testing properly mirrored the impact of effective overburden pressure.

2. Site Selection and Geological Background

The selected study sites covered diverse geological and soil environments throughout Thailand.

The soil in Bangkok consists of loosely compacted alluvial clay that typically develops in coastal plains. The depth of this soft to very soft clayey soil ranges between 16 – 25 m. The present study implemented down-hole seismic testing at 6 different sites across Bangkok.

In the eastern part of Thailand Maptaphut (MTP) maintains a reputation for industrial activities while offering soil conditions that combine clayey and sandy deposits. Five down-hole seismic tests took place throughout this area.

The geologic profile of Chiang Mai includes a range of loose sandy and silty deposits along with intermittent clay layers in Northern Thailand. Soil sampling and classification formed the basis of baseline investigations during the extensive geotechnical testing at these sites. Staff drilled two boreholes for testing.

3. Analysis of Down Hole Seismic Test

In a down-hole seismic test, the travel time of a shear wave, generated at a distance X on the ground surface (Fig. 1), is recorded by a receiver placed in a pre-drilled borehole. Several algorithms can be used to analyze the down-hole data obtained from this process. For example, Ferdinando and Angelo [15] employed a sophisticated probabilistic model to address the variation in shear wave velocity obtained from down-hole seismic tests. However, in their study, a simple multi-linear time-depth plot analysis was used to compute the down-hole seismic test results. As will be demonstrated later in this paper, this method is not sufficiently accurate to provide a comprehensive understanding of subsoil shear wave velocity and stratification. It lacks the precision needed to capture the complexities of soil layers, potentially leading to an incomplete or inaccurate representation of the subsurface conditions. Another well-known methodology is the harmonic average profile [16, 17]. This approach uses the accumulated arrival time to compute the shear wave velocity profile from down-hole test data. By considering the harmonic mean of the velocities over the depth intervals, this method provides an alternative means of averaging that can account for the varying speeds in different soil layers, offering a more accurate representation of the overall velocity profile.

An example of the shear wave velocity profile given in Passeri et al. [17] obtained from this method compared to conventional one is shown in Fig. 3.

In the present study, four simple calculation methods were used comparatively to assess their effectiveness in reflecting the influence of effective stress on shear wave velocity. Those are briefly given below.

3.1. Method 1:Multi-linear Time-Depth Plot Analysis

This is the conventional method widely adopted in analysis of down-hole seismic data. In this method, the shear wave velocity profile is obtained by plotting the travel time of the shear wave against the depth of the receiver. The travel time is measured from the point where the shear wave is generated at the surface to various depths in the borehole. The data points on this plot are then connected using multiple linear segments. Each segment represents a different layer or set of layers in the subsoil, characterized by a relatively constant shear wave velocity (Fig. 4).

DOI:10.4186/ej.2025.29.6.1

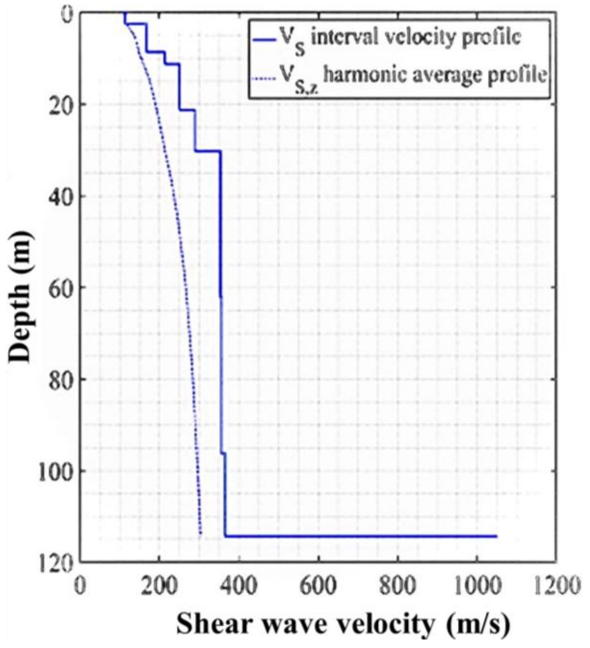


Fig. 3. Comparison between shear wave velocity profiles from harmonic average and conventional profile reproduced from Passeri et al. [17].

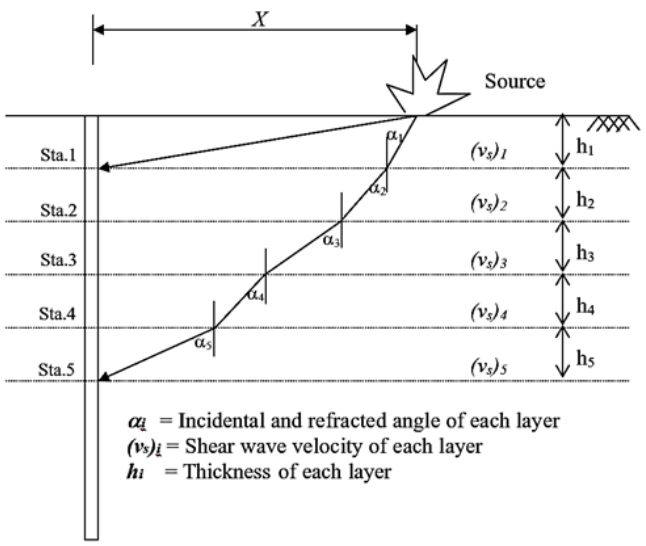


Fig. 4. Schematic representation of shear wave propagation in a down-hole seismic test illustrating the source position, wave paths, refraction angles (αi), and measurement stations across multiple soil layers.

The slope of each line segment in the travel time-depth plot corresponds to the inverse of the average shear wave velocity for that segment. Thus, by determining the inclination (slope) of these lines, an average value of shear wave velocity can be calculated for each group of data points that exhibit similar inclinations as present in Fig. 5. This method is commonly used because it provides a straightforward way to approximate the average shear wave velocity across different soil layers. However, it does not explicitly account for variations in effective stress, which can influence the velocity.

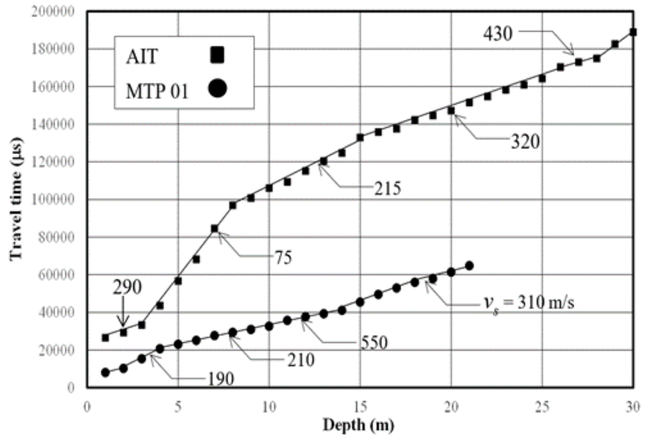


Fig. 5. Time-depth plots used for shear wave velocity determination at two different sites (AIT and MTP-01), showing the multi-linear segments representing different soil layers and their corresponding velocities.

3.2. Method 2: Depth-Time Difference Ratio

This method calculates shear wave velocity by taking the ratio of the vertical distance between two adjacent measurement points along the borehole to the time difference of the shear wave's travel between these points. The formula used is:

$$(v_s)_i = \frac{z_i - z_{i-1}}{t_i - t_{i-1}} \tag{4}$$

where

$(v_s)_i$ is shear wave velocity

z_i is depth

t_i is arrival time at measurement point i

This method is commonly employed in seismic cone testing, where two receivers are fixed at a predetermined vertical interval—typically 1.0 m—along the probe casing to capture wave propagation signals [18]. Although widely used, previous studies [19] have shown that this approach often leads to overestimated shear wave velocities, particularly in near-surface layers and at soil interfaces. These inaccuracies primarily stem from abrupt stiffness variations between adjacent layers. Furthermore, Akin et al. [20] highlighted that such simplified interpretations of down-hole and up-hole data are generally insufficient for reliable geotechnical assessments involving complex subsurface conditions.

This method provides a more localized measurement of shear wave velocity compared to Method 1, as it calculates the velocity between specific intervals rather than averaging over larger depths. This can be particularly useful for detecting variations in soil properties and identifying changes in shear wave velocity due to different stress conditions. However, like Method 1, it may not fully capture the effect of varying effective stresses unless these stress changes correlate with changes in shear wave velocity.

3.3. Method 3: Trigonometric Distance and Time Difference

In this method, the shear wave velocity is determined by calculating the trigonometric distance (considering the horizontal offset of the wave source from the borehole) and the corresponding travel time difference. The formula can be expressed as:

$$(v_s)_i = \frac{\sqrt{X^2 + z_i^2} - \sqrt{X^2 + z_{i-1}^2}}{t_i - t_{i-1}} \tag{5}$$

where X is the horizontal distance from the source on the surface to the center of the borehole.

This method accounts for the fact that the source of the shear wave is not directly above the measurement points, providing a more accurate representation of the travel path and thus the velocity. It can effectively reduce errors at shallow depths and interfaces, offering results comparable to more complex methods while being relatively straightforward to implement.

3.4. Method 4: Virtual Interface Method

This refined method assumes that each measurement station in the borehole acts as a virtual interface where the shear wave undergoes refraction. The calculation considers the shear wave's travel time and path as if the wave is refracting at each station, effectively simulating how the wave velocity changes due to variations in soil properties and effective stress states. Teachavorasinskun and Lukkunaprasit [13] refined the calculation procedure by modeling each measurement point (station) as a virtual interface where the incident wave refracted, as illustrated schematically in Fig. 1.

The virtual interface approach allows for a detailed analysis of the shear wave velocity profile, potentially capturing the effects of effective overburden stress more accurately. It considers the changes in shear wave velocity across different layers, considering the stress conditions at each virtual interface [13, 21]. This method can be particularly useful in complex stratified soils where significant changes in stress conditions and soil properties are. The method aims to correct errors associated with the interface by accounting for wave refraction at these virtual boundaries.

Snell's Law:

$$\frac{\sin\alpha_1}{(v_s)_1} = \frac{\sin\alpha_2}{(v_s)_2} = \frac{\sin\alpha_3}{(v_s)_3} = \ldots\ldots = \frac{\sin\alpha_n}{(v_s)_n} \tag{6}$$

Geometrical Equation:

$$X = \sum_{i=1}^{n} h_i \tan\alpha_i \tag{7}$$

Traveling Time Equation:

$$t = \frac{1}{(v_s)_1}\left(\sum_{i=1}^{n} \frac{h_i}{\cos\alpha_i}\frac{\sin\alpha_1}{\sin\alpha_i}\right) \tag{8}$$

where

X is horizontal distance from the source on the surface to the center of the borehole

h_i is thickness of each layer

α_i is incidental/refraction angles

i is measurement station = 1, 2, 3, ….., n

n is number of layers under consideration

t is recorded travel time at layer n

$(v_s)_i$ is shear wave velocity of each layer above the virtual layer n

$(v_s)_n$ is unknown

The shear wave velocity at any specific depth (i.e., measurement point, *n*) is determined by solving the above three fundamental wave equations simultaneously. Teachavorasinskun and Lukkunaprasit [19] demonstrated that this modified approach effectively reduced errors at soil layer interfaces. However, their validation was based on only three down-hole tests conducted in Bangkok, which is a limited sample size for drawing broad conclusions.

In this paper, we extend the previous research by incorporating an additional 10 down-hole seismic tests conducted across three distinct regions in Thailand: the Bangkok Metropolitan area, the Maptaput Industrial Estate (MTP) in Rayong province along Thailand's eastern seaboard, and Chiang Mai province in the northern part of the country. Each test maintained a consistent measurement distance of 3.0 meters from the borehole. This expanded dataset aims to comprehensively evaluate the influence of overburden pressure on shear wave velocity and to rigorously assess the effectiveness of the proposed computational methods for analyzing shear wave propagation in varied geological settings.

4. Results and Discussions

Figures 6 and 7 show how different methods calculate shear wave velocity profiles between previously analyzed approaches. Two boreholes supplied the data which came from Maptaphut and Bangkok areas. The subsoil profiles for all the sites appear in the accompanying figures as a point of reference.

Method 1 measures average shear wave velocity through the analysis of travel time at different depths. This method fails to incorporate effective overburden stress as a factor in determining shear wave velocity profiles. Effective overburden stress has a substantial impact on soil layer stiffness and shear wave velocity at deep levels but the current method excludes this important factor. Consequently this omission creates inaccuracies in the estimation results. The shear wave velocity profile measured by this method fails to show the actual in-situ soil characteristics and true dynamic properties of the soil.

The simple calculation method (Method 2) produces abnormal shear wave velocity readings that increase dramatically in both surface areas and shallow soil layer interfaces. Figure 3 demonstrates three distinct shear wave velocity increase zones that occur (1) at the surface layer and (2) at the SM-SC interface followed by (3) an additional increase in the SC layer where Standard Penetration Test (SPT) values display a sudden decrease. The method produces unrealistic shear wave velocity readings in a Bangkok area borehole which become most pronounced near the surface and at the clay-sand interface depths. The Bangkok area consists of a shallow clay layer extending 15-20 meters below the surface which shows uniform characteristics between soft and medium stiffness. The trigonometric distance method (Method 3) provides a solution to reduce the overestimated shear wave velocity found at the ground surface. The method continues to produce some errors when measuring shallow soil layers but it reduces these errors.

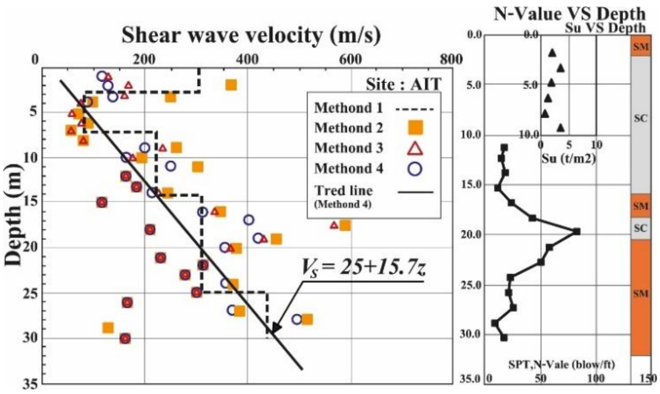


Fig. 6. Comparison of shear wave velocity profiles calculated using four different analytical algorithms at a site in Eastern Thailand (Maptaphut), with corresponding soil profile and SPT N-values shown on the right.

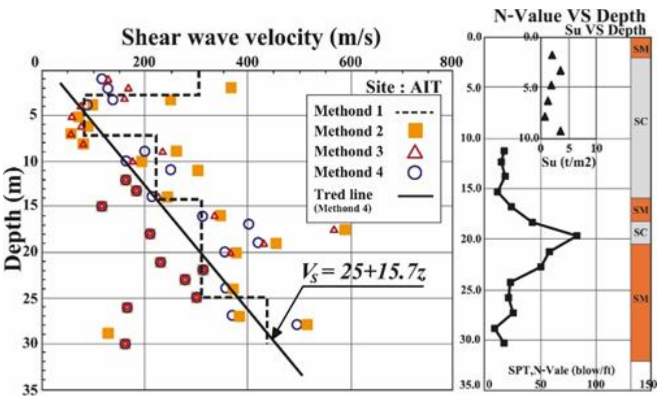


Fig. 7. Comparison of shear wave velocity profiles obtained from four analytical algorithms at a site in Central Thailand (Bangkok), with corresponding soil profile and SPT N-values shown on the right.

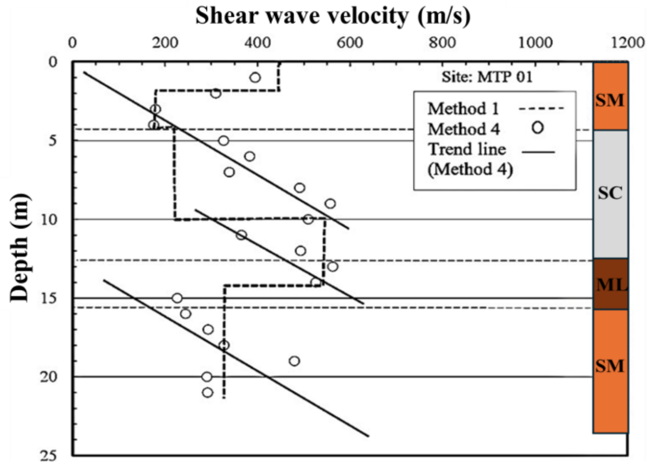
The refined calculation technique that integrates Method 3 and Method 4 classical principles produces improved results when compared to the basic method. This refined method allows shear wave velocity to shift between soil layers more smoothly thus preventing unrepresentative changes at layer interfaces. Soil layers stratification stands clear for observation with this method. The method delivers better results for stress-dependent soil characteristics because it considers the changes that effective overburden stress causes within the soil. Improved assessment results become achievable through this modified approach which delivers a highly detailed representation of soil dynamics for better shear wave velocity profile accuracy.

Method 3 demonstrates trigonometric distance calculation results which approximate the data output of Method 4. The results obtained from Method 4 will serve as the main basis for discussion moving forward. The method ensures complete evaluation of diverse computational approaches for analysis and comparison.

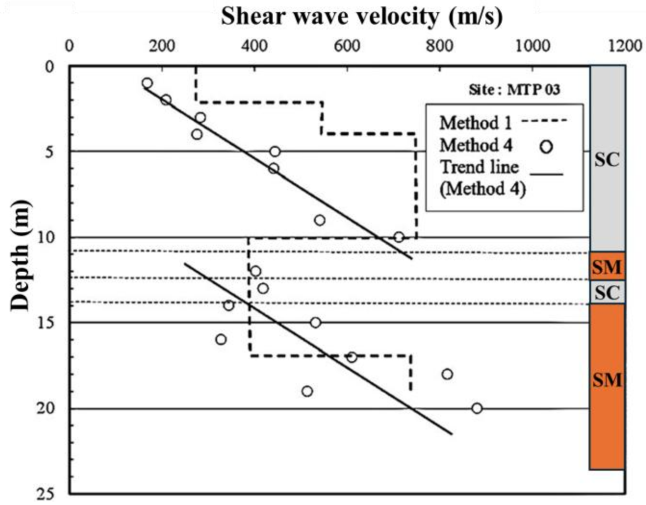
The refined analytical method generated shear wave velocity profiles from two MTP area borehole tests which are shown in Fig. 8. The shear wave velocity shows three separate linear trends which become visible in Fig. 8(a). The profiles show how various soil layers contain a thin clayey section sandwiched between sand layers thus enabling precise characterization of the stratified soil profile. The shear wave velocity distribution throughout these layers appears in separate profiles that demonstrate how the clayey seam influences overall velocity distribution.

In contrast, Fig. 8(b) illustrates a site primarily composed of sandy soils, where two separate shear wave velocity profiles are necessary to accurately express the soil stratification. In general, the shear wave velocity profiles in the Mataphut area can be represented by two profiles; namely the upper layer and lower layer profiles. It should be emphasized herein that this approach captures the variations in shear wave velocity within the predominantly sandy soil, providing detail insight into how different depth intervals and layer stratification affect the shear wave velocity profile.

Although these profiles are relatively straightforward to establish for each tested site, the coefficients derived from these analyses exhibit noticeable variability. This variability presents challenges in achieving a uniform representation across the entire area, as differences in soil properties and stratification at each location influence the resulting shear wave velocity profiles. While these profiles provide valuable insights into local subsurface conditions, they also highlight the inherent complexity in developing a generalized model that reliably captures the diversity of soil behavior in the Maptaphut (MTP) region. Comparable issues have been reported in other geological contexts, where probabilistic modeling approaches have been applied to address the uncertainties associated with site-specific shear wave velocity variations [22].



(a)



(b)

Fig. 8. Variation of shear wave velocity with depth at Maptaphut area showing (a) site with thin clayey section between sand layers and (b) site primarily composed of sandy soils, with soil stratification indicated by different shading.

Since the shear wave velocity (or shear modulus) does not linearly depend on the overburden stress (or depth), the correlation between shear wave velocity and depth should assume a similar functional form as shown in Eq. (1). Due to large data scattering, it is easier to illustrate the correlations between shear wave velocity and depth using the logarithmic plot. Therefore, the shear wave velocity profile should be expressed as follows:

$$log(v_s) = \log(K) + m\,log(z) \tag{9}$$

The parameter K is a parameter related to the strength of the soil structure at a unit depth (e.g., 1 meter), which varies according to mineral composition, formation history, and soil particle arrangement. The K value represents the intercept of the regression line, while *m* is the slope. Higher K values indicate soils with greater inherent strength. For instance, in the Maptaphut area at depths less than 10 meters, K values range between 100-160, reflecting stronger soil characteristics compared to Bangkok clay with a K value of only 12.52. The Bangkok subsoil is predominantly composed of soft to very soft clay with limited stratification down to approximately 15–20 meters. The logarithmic relationship between shear wave velocity and depth yields low K values for Bangkok clay, such as 12.52, indicating weak inherent stiffness. This finding is consistent with earlier studies reporting low stiffness characteristics and poor engineering behavior of Bangkok clay under low confining pressure conditions [23].

This aligns with findings from Arjwech et al. [11], which showed that the engineering properties of soils correlate directly with measured shear wave velocities. Thus, K can effectively serve as an indicator of the basic engineering properties of soils in different areas.

Figures 9(a)–9(d) provide a summary of the logarithmic profiles of shear wave velocity from all down-hole tests conducted in this study, along with the subsoil profiles representing the tested sites. Table 1 summarizes the coefficients, *m* and *K*, obtained from all tested sites. The following observations can be made:

The inclination *m* and constant *K* in the shear wave velocity profile account for the effects of unit weight (including) hydrostatic underground water pressure and soil type, respectively. As previously discussed, variations in these two parameters reflect the stratification characteristics of the subsoil layers, including changes in the hydrostatic pressure within each layer. Although direct physical evidence is lacking, it is noteworthy that Figs. 9(b)–9(d) suggest potential abrupt changes in pore water pressure. For instance, a rapid increase in pore water pressure, possibly due to the presence of a confined aquifer, can lead to significant alterations in the inclination *m* and constant *K* compared to their values in the upper layers. This influence of pore water pressure is particularly evident in Fig. 9(d), where the presence of sand layers interspersed between clayey soil layers may create a confinement effect, thereby impacting the shear wave velocity profile.

A single shear wave velocity profile can be obtained for the Bangkok area, excluding variations caused by the topmost 2–3 m of stiff crust (Fig. 9(a)). The Bangkok area exhibits minimal stratification at shallow depths and generally consists of uniform soft-to-medium clay extending down to about 15–20 m.

The MTP area is divided into two sub-regions based on the best-fitted values of *K* and *m*, though the differences are minor. Generally, two shear wave velocity profiles are distinguished, separated at depths of about 10 m from the surface. These profiles suggest that soil layers deeper than 10 m may be influenced by confined groundwater pressure. This extra confined pore water pressure in the sandy soil may be caused by thin clayey seams between the sand layers, which could also explain the shear wave velocity profiles obtained from sites in Chiang Mai province (Fig. 9(d)). The differences in the inclinations of the upper and lower lines are attributed to the effects of confined pore water pressure in the logarithmic plot.

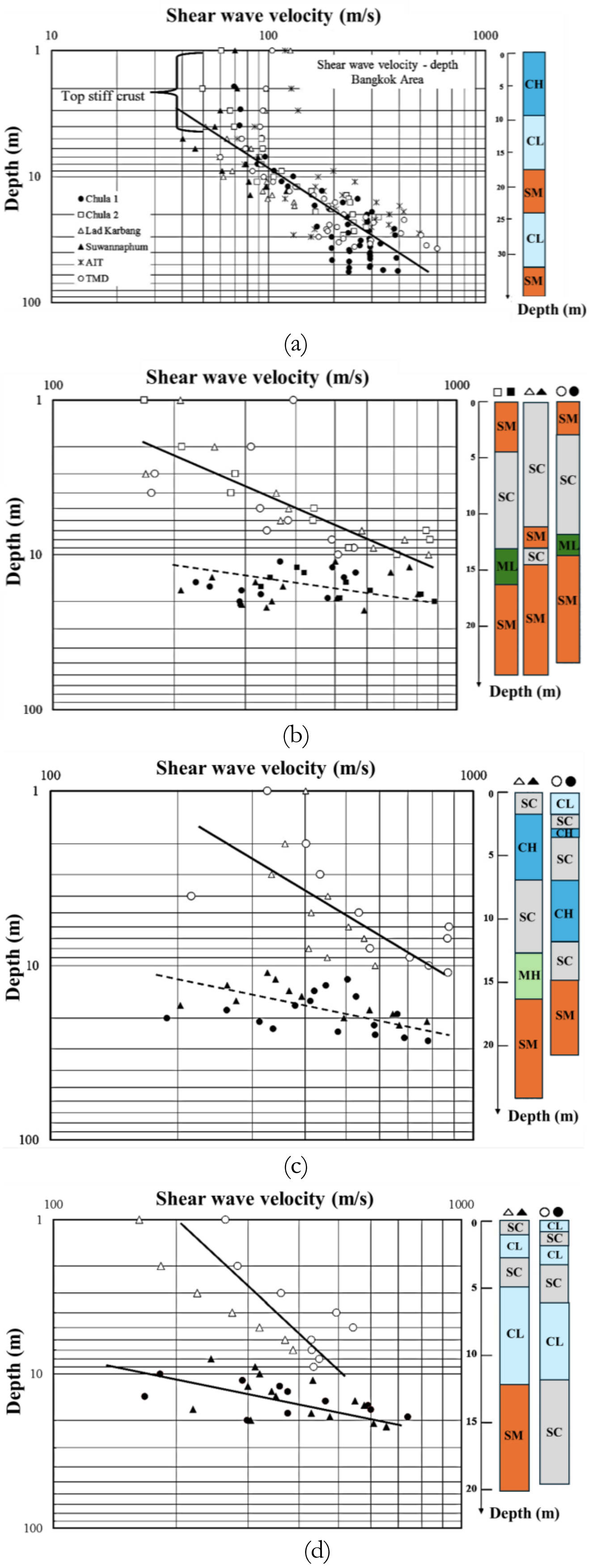


Fig. 9. Shear wave velocity profiles obtained from down-hole tests (a) Bangkok area (b) Maptaphut area I (c) Maptaphut area II (d) Chiang Mai area.

The site-specific relationship expressed in Eq. (9) offers vital practical utility to engineers working in civil and geotechnical fields. This relationship enables cost-effective and time-efficient surveying of large areas because testing at limited points establishes suitable K and m values for the entire region. Engineers can compute shear wave velocity measurements at different depths using the acquired data without requiring further tests.

The stability assessment of high-rise building foundations in Bangkok's soft clay layer base requires understanding velocity-depth profiles reaching depths of 15-20 meters below the surface. Through the application of K=12.52 and m=2.9 values discovered in this research, foundation engineers can perform rapid shear wave velocity assessments during design work to create more effective structures. The relationship between depth and shear wave velocity enables urban planners to evaluate earthquake risks, thus helping them define zones suitable for distinct building construction types.

Arjwech et al. [24] demonstrated that using multiple geophysical techniques together, such as 2D ERT combined with shear wave velocity measurements from down-hole seismic testing, can increase accuracy in identifying potentially collapsible soil layers, which aids in designing safer foundation structures. The relationship between shear wave velocity and depth found in this study can combine with other geophysical methods to create more efficient construction site geotechnical characterization.

The shear wave velocity profile obtained in this research features unique site characteristics that enable specific site evaluation. Site-specific information emerges from this method to deliver precise descriptions of subsurface conditions which align with the geological and stress characteristics of individual sites. Engineers gain a localized view of soil property and overburden stress effects on shear wave velocity through observing varying coefficient values across different areas.

Down-hole seismic tests measure shear wave velocity depending on stress conditions according to these results. The dependency of stress on these measurements remains minor in comparison to documented laboratory results that demonstrate stronger stress-related effects. The measurement gap demonstrates why field conditions require special attention during the application of laboratory models to actual field operations. Engineers now have better capabilities to make precise decisions using site-specific shear wave velocity profiles which results in improved geotechnical assessment reliability and design integrity. The experimental outcomes demonstrate that ignoring effective stress can degrade quality of shear wave velocity field measurement results. Traditional implementation methods prove simple to execute but fail to address real-world conditions properly which results in incorrect assessment results. The virtual interface method delivers precise and dependable shear wave velocity measurements since it handles overburden pressure explicitly.

The current study contrasts with Kim et al [2] on down-hole seismic tests through multiple distinct aspects although both studies utilize similar analytical tools. The main differences are: (1) this research focuses on applying analysis methods in the context of various regions in Thailand with vastly different geological characteristics, whereas Kim et al. [2] used synthetic models for parametric studies, while this research uses data from actual field tests; (2) this study developed and improved the virtual interface method by placing greater emphasis on the effects of overburden pressure on shear wave velocity measurements, which differs from Kim's method [2] that emphasizes Snell's Law without clearly focusing on overburden pressure effects; and (3) this research developed site-specific relationships between shear wave velocity and depth for various areas in Thailand, filling gaps in knowledge about soil behavior in Southeast Asia.

The relationship between shear wave velocity and SPT-N value becomes applicable when in-situ soil properties are already established. All MTP sites display a relationship between shear wave velocity and SPT-N value which is illustrated in Fig. 10. Research reveals an overall pattern of correlation between shear wave velocity and depth at $V_s = 198\ N^{0.24}$ which explains 56% of the data points variability. Researchers report comparable findings about data diversity and the relationship between shear wave velocity and SPT-N values in their publications [13, 17].

Table 1. Summarize of parameters for determination of shear wave velocity profiles.

Location	Depth	*m*	*K*
Bangkok	0 - 60 m	0.90	12.52
Maptaphut Area I	0 - 10 m	0.99	100
	> 10 m	2.63	1.53
Maptaphut Area II	0 - 10 m	0.57	160
	> 10 m	1.96	1.09
Chiang Mai	0 - 10 m	1.82	0.94
	> 10 m	0.52	60

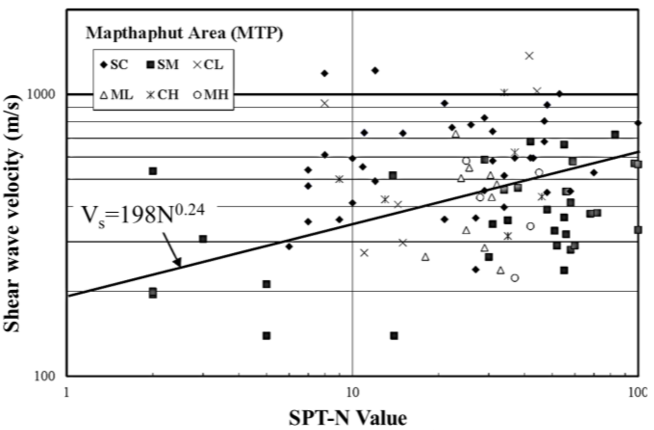


Fig. 10. Correlation between shear wave velocity and SPT N-value obtained from down-hole tests conducted in MTP area.

5. Limitations and Recommendations for Future Research

This research has some limitations that should be considered when applying the results. First, the number of test sites is limited, but they span key geological characteristics in Thailand. Second, the analysis does not consider seasonal changes in groundwater levels, which may influence the efficacy of overburden pressure. Third, soil moisture content was found to influence shear wave velocity significantly, but we did not systematically control or measure moisture content.

This study's scope should be expanded for future research to include more diverse areas and soil types, particularly in areas with high seismic risk or where the soil is prone to collapse. Furthermore, long-term studies should be carried out to observe variations in shear wave velocity at different loading conditions and moisture contents and to correlate the results with other technical parameters such as soil settlement and deformation.

More research is needed on the effect of permanent soil structure changes due to loading on shear wave velocity to improve the understanding of soil behavior under seismic loading. As Arjwech et al. [10] recommended, integrating multiple geophysical techniques (integrated geophysical approach) may enhance the accuracy of soil engineering property assessments and overburden pressure effects.

6. Conclusions

The evaluation of shear wave velocity from down-hole seismic data fails to provide accurate sub-soil stratification results when soil layer boundaries exist near the surface. The new method which considers each measurement point as a virtual point of shear wave refraction has demonstrated its effectiveness for reducing measurement errors both near the surface and at the interfaces between soil layers. The method delivers improved shear wave velocity precision by handling the diverse characteristics associated with soil stratification and property variations. The calculation method based on trigonometric distance functions accurately determined shear wave velocity for sites with basic stratification layers when the depths remained uncomplicated. The calculation technique determines shear wave velocity by using the horizontal separation between source and measurement point which provides an efficient method for basic applications.

The shear wave velocity obtained from down-hole seismic tests throughout different Thai locations benefits from these analytical advancements, which better represent overburden pressure effects. The detailed interpretation technique enables researchers to obtain dependable velocity results, which simultaneously generate insights about local geological site features. Detailed analysis provides better subsurface condition characterization abilities that support engineering and construction decisions.

Acknowledgement

This research is supported by the Rachadaphiseksomphot Endowment Fund, part of the "Strengthen Chulalongkorn University Researcher's Project" and the Thailand Research Fund (TRF : RMU5180052).

References

[1] R. Salgado, V. P. Drnevich, A. Ashmawy, W. P. Grant, and P. Vallenas, "Interpretation of large-strain seismic cross-hole tests," *Journal of Geotechnical and Geoenvironmental Engineering ASCE*, vol. 123, no. 4, pp. 382–388, 1997.

[2] D. S. Kim, E. S. Bang, and W. C. Kim, "Evaluation of various downhole data reduction methods for obtaining reliable VS profiles," *Geotechnical Testing Journal*, vol. 27, no. 6, pp. 585–597, 2004.

[3] B. O. Hardin and V. P. Drnevich, "Shear modulus and damping in soils: Measurement and parameter effect," *Journal of Soil Mechanics and Foundations Engineering ASCE*, vol. 98, no. 6, pp. 603–624, 1972.

[4] T. Iwasaki, F. Tatsuoka, and Y. Takagi, "Shear moduli of sands under cyclic torsional shear loading," *Soils and Foundations*, vol. 18, no. 1, pp. 39–51, 1978.

[5] S. K. Roesler, "Anisotropic shear modulus due to stress anisotropy," *Journal of the Geotechnical Engineering ASCE*, vol. 105, no. 7, pp. 871–880, 1979.

[6] P. Yu and F. E. Richart, "Stress ratio effects on shear modulus of dry sands," *Journal of Geotechnical Engineering ASCE*, vol. 110, no. 3, pp. 331–345, 1984.

[7] S. Teachavorasinskun, P. Thongchim, and P. Lukkunaprasit, "Shear modulus and damping of soft Bangkok clays," *Canadian Geotechnical Journal*, vol. 39, no. 5, pp. 1201–1208, 2002.

[8] S. Likitlersuang, S. Teachavorasinskun, C. Surarak, E. Oh, and A. Balasubramaniam, "Small strain stiffness and stiffness degradation curve of Bangkok clays," *Soils and Foundations*, vol. 53, no. 4, pp. 498–509, 2013.

[9] D.-L. Presti, F. Francesco, P. Massimiliano, P. Ermanno, S. Massimiliano, and S. Stefano, "Use of seismic piezocone for the assessment of the propagation velocity of body waves," *Rivista Italiana di Geotecnica*, vol. 58, no. 2, pp. 90–98, 2024.

[10] B. Wair, J. T. DeJong, and T. Shantz, "Guidelines for estimation of shear wave velocity profiles," PEER Report 2012/08, Pacific Earthquake Engineering Research Center, 2012.

[11] R. Arjwech and P. Sriwangpon, "Evaluating the engineering properties of loess soil using seismic methods," *Songklanakarin Journal of Science and Technology*, vol. 43, no. 1, pp. 259–268, 2021.

[12] S. Teachavorasinskun and T. Amornwithayalax, "Elastic shear modulus of Bangkok clay during undrained triaxial compression," *Geotechnique*, vol. 52, no. 7, pp. 537–540, 2002.

[13] S. Teachavorasinskun and P. Lukkunaprasit, "Stress induced and inherent anisotropy on elastic stiffness of soft clays," *Soils and Foundations*, vol. 48, no. 1, pp. 127–132, 2008.

[14] T. E. Fumal, "Correlations between seismic wave velocities and physical properties of near-surface geologic materials in the southern San Francisco Bay region," USGS Open File Report 78-1067, 1978, pp. 1–114.

[15] T. Ferdinando and A. Angelo, "Probabilistic shear wave velocity model based on downhole test database for Apennine flysch formations," *Soil Dynamics and Earthquake Engineering*, vol. 173, Art. no. 108132, 2023.

[16] L. T. Brown, D. M. Boore, and K. H. Stokoe, "Comparison of shear-wave slowness profiles at 10 strong-motion sites from noninvasive SASW measurements and measurements made in boreholes," *Bulletin of the Seismological Society of America*, vol. 92, pp. 3116–3133, 2002.

[17] F. Passeri, F. Sebastiano, and R.-M. Adrian, "A new geostatistical model for shear wave velocity profiles," *Soil Dynamics and Earthquake Engineering*, vol. 136, Art. no. 106247, 2020.

[18] R. G. Campanella and W. P. Stewart, "Downhole seismic cone analysis using digital signal processing," in *Proceedings of the 2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*, vol. 1, no. 1.32, pp. 77–83, 1991.

[19] S. Teachavorasinskun and P. Lukkunaprasit, "A simple correlation for shear wave velocity of soft Bangkok clays," *Geotechnique*, vol. 54, no. 5, pp. 323–326, 2004.

[20] M. K. Akin, S. L. Kramer, and T. Topal, "Empirical correlations of shear wave velocity (Vs) and penetration resistance (SPT-N) for different soils in an earthquake-prone area (Erbaa-Turkey)," *Engineering Geology*, vol. 119, pp. 1–17, 2011.

[21] J. P. Sully and R. G. Campanella, "Evaluation of in-situ anisotropy from crosshole and downhole shear wave velocity measurement," *Geotechnique*, vol. 45, no. 2, pp. 267–282, 1995.

[22] F. Totani and A. Aloisio, "Probabilistic shear wave velocity model based on downhole test database for Apennine flysch formations," *Soil Dynamics and Earthquake Engineering*, vol. 173, Art. no. 108132, 2023.

[23] F. Shibuya, H. Tanaka, M. Tanaka, and K. Hamonche, "Bi-country co-operative research programme on geotechnical engineering properties of Bangkok clay," Chishitsu-to-Chosa, vol. 72, pp. 44–51, 1997.

[24] R. Arjwech, S. Tamasa, S. Eua-Apiwatch, and P. Sriwangpon, "A study of geophysical techniques for identifying collapsible soil strata," *International Journal of Geotechnical Engineering*, vol. 10, no. 1, pp. 1–12, 2025.

Sirichai Pethrung is a lecturer at the Department of Civil Engineering, Faculty of Engineering, Rajamangala University of Technology Krungthep. He received his M.Eng. and Ph.D in Civil Engineering from the Chulalongkorn University. His research interests include soil dynamic properties and design of seismic resistances.

Supot Teachavorasinskun is a professor at the Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Thailand. He received his M.Eng. and D.Eng. in Civil Engineering from the University of Tokyo, Japan in 1992. His research interests include soil dynamic properties and design of seismic resistances.

Sitthiphat Eua-apiwatch is an assistant professor at the Department of Civil Engineering, Faculty of Engineering, Burapha University, Thailand. He received his Ph.D in Civil Engineering from the Chulalongkorn University, Thailand in 2013. His research interests include subsurface utility engineering, geoenvironmental, and geotechnical engineering.