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Original Article

Evaluating the engineering properties of loess soil using seismic methods

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Abstract

Loess covers most areas of Khon Kaen University campus, northeastern Thailand. It is identified as a collapsible soil. This study aims to find the engineering properties of loess using multi-channel analysis of surface wave (MASW) and downhole seismic methods. MASW results show that the shear wave velocity varies from 242 to 329 m/s while the compressional wave velocity is 371 to 740 m/s. The results of downhole method show that shear wave velocity ranges between 210 and 323 m/s, while the compressional wave velocity varies from 420 to 771 m/s. The derived body wave velocity from MASW method varies by 25% from that obtained using the downhole method. Young's modulus calculated from these results was validated with information from previous research and larger than those of determining via static geotechnical tests. The MASW method is a relatively cost-effective method, so it can be applied as an alternative to geotechnical testing when determining soil elastic properties.

Keywords: Multi-channel Analysis of Surface Wave (MASW), shear wave, downhole seismic method, Khon Kaen University, loess

1. Introduction

Loess covers most of the northeastern region of Thailand including Khon Kaen university campus (Phien-wej, Pientong, & Balasubramaniam, 1992). It is a predominantly a silty sediment, sometimes with minor sand and clay fractions, which is transported by wind and often found as deposits in Quaternary semi-arid environments (Boonsaner, 1977, 2002; Chong, 1988). Loess is classified as slightly to moderately dispersive (Gasaluck, Luthisungnoen, Angsuwotai, Muktabhant, & Mobkhuntod, 2000) that recognized as a collapsible soil as its load capacity can be reduced abruptly with increasing moisture content (Terzaghi & Peck, 1948).

Loess deposits can be classified into two types, red and yellow that are similar in lithology and mineralogy but different oxidation states causes different colors (Phien-wej *et al.*, 1992). Khon Kaen red loess is non-plastic red sandy silt or silty sand (SM-SC), 65% sand, 30% silt and 5% clay. Most of the soil particles are 0.005 to 0.042 mm in size with poorly sorted particles. Loess is unconsolidated and has a loose to medium density. When moisture content increases, it causes to decrease the shear strength parameters (Punrattanasin, Subjarassang, Kusakabe, & Nishimura, 2002; Sinchai, 2002; Udomchoke, 1991). Natural dry density is 1,500 kg/m^3 (Chong, 1988). From plate load test, Young’s modulus is 22.6 and 6.4 MPa under wet and soaked conditions, respectively. Young’s modulus is between 29.0 and 19.6 MPa from triaxial tests when the moisture content is between 6% and 12% (Sinchai, 2002) and between 69.2 and 83.2 MPa studied by Phien-wej *et al.* (1992). Poisson ratio is between 0.38 and 0.42 (Udomchoke, 1991).

There are 277 buildings on the Khon Kaen University campus (in 2009), and almost all of buildings are employed by shallow foundations to support the building structures. However, subsidence of some of the buildings occurred due to instability of the underlying red loess (Juntarasom, 2015). The loss of structural integrity is attributed to increases in moisture content (Kesawadkorn, 2000; Prohmriang, Lerthanasangtum, Suriyavanagul, & Pukdekssem, 1997). Moreover, severe problems with settlements and low-rise buildings were caused by leakings from drains and sewers (Sarujikumjonwattana,

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Malapet, & Sertwicha, 1987). Consequently, foundation systems on campus often needed to be rebuilt, causing construction costs to increase. For this reason, soil property testing is necessary to be carried out before construction projects begin.

The testing of soil properties can be separated into two main approaches. The first one is a wide-area survey without soil sampling consisting of geophysical methods (e.g. seismic or electrical techniques) and geotechnical engineering methods (e.g. SPT and FVT techniques). The second approach involves soil sampling in which samples are collected to identify their properties in the laboratory (e.g. tri-axial and plate load tests). Most geophysical methods can be operated as non-destructive techniques; furthermore, they are less time-consuming and relatively cost-effective compared to conventional geotechnical testing (Anderson, Croxton, Hookver, & Sirles, 2008; Arjwech *et al*., 2013). The applicability of a non-destructive geophysical method to ascertain engineering properties of collapsible loess soils is investigated in this research.

Herein, the non-destructive multi-channel analysis of surface wave (MASW) technique was used to measure the spatially-averaged elastic moduli of loess based on body wave velocities extracted from seismic records. The minimally destructive downhole seismic method was conducted to compare its determination of the elastic moduli with the corresponding results obtained with the MASW method. This paper is considered an attempt to understand the static soil parameters determined by dynamic soil parameters and measured by geophysics methods.

2. Study Area and Geology

The study area is located in the northern part of Khon Kaen University campus, Khon Kaen province, northeastern Thailand. The near surface is composed of unconsolidated sediments categorized as Quaternary alluvial and Quaternary terrace soils. Loess and gravel deposits were found locally on the terrace with thicknesses that varied from a few meters to more than 5 m (Arjwech, Wanakao, & Everett, 2019). Shear wave studies were conducted at three locations where thick loess deposit was previously studied (Sinchai, 2002) and subsidence of nearby buildings was reported (Juntarasom, 2015). Three boreholes were drilled and prepared for the measurement. They are located on the highest part on the campus. The first area (DH1) is located beside a baseball field, the second area (DH2) is located adjacent to the Institute of Administration Development and the third area (DH3) is located on a demonstration field of the Faculty of Agriculture (Figure 1). The boreholes penetrated to depths ranging from 15 to 33 m. They were identified to be dry during the downhole test.

The terrain morphology of the study area is characterized as middle to high river terrace, covered with the gravel lithofacies (Qt) of middle Pleistocene age shown in Figure 2 (Wannakao *et al*., 2001). This sedimentary unit consists of sand and gravel beds which can be separated into three distinct layers as can be seen in Figure 3. The top layer consists of particles of the small grain sizes of low to medium dense red sand (SM) and thickness is between 2.5 and 10 m. The middle layer is identified as relatively younger gravel. It is comprised of gravelly laterite on top of the layer and dense to very dense gravel with fragment of petrified wood. Its thickness is between gravel. It contains dense gravel with petrified wood. Its thickness is between 3 and 30 m (Boonsaner, 1977; Boonsaner & Tassanasorn, 1983; Sinchai, 2002).

3. Methodology

In this research, Multi-Channel Analysis of Surface Wave (MASW) and downhole (surface-to-borehole) seismic tests were conducted on outcrops of loess (Figure 4).

3.1 Multi-channel Analysis of Surface Wave

MASW is a seismic technique executed on the ground surface to characterize the near-surface (e.g., ≤30 m) Vs distribution. It is designed to investigate utilizing the Rayleigh surface wave that is identified as the strongest seismic wave. The technique is determination of the wave dispersion curve (different frequencies travel at different velocities), which in turn is inverted for the shear wave velocities of the soil layers (Park, Miller, Ryden, Xia, & Ivanov, 2005; Park, Miller, & Xia, 1999).

The MASW data were recorded using an array of 24 single-component 4.5-Hz geophones with 1 m spacing. The data were gathered by laptop via a 24-channel Geometrics Geode. The MASW data acquisition included both active and passive measurements. All six lines were surveyed for the 2D Vs evaluation that generated 2D Vs maps showing both lateral and vertical change. At BH1 and BH2, the two profiles intersect and the location of borehole is about the middle of the lines. At BH3, the two profiles were not intersected due to restriction of geophone deployment. Surveys were performed in April 2017.

For the active method, a seismic signal (Figure 5a) was generated by a sledgehammer struck vertically onto a metal plate at 5 m offset from the closest receiver geophone. The total length of a survey line is 23 m, which generates less than 12 m depth of investigation (Aizawa, 2014). The passive method involves an analysis of lower frequency (1-30 Hz) surface waves recorded by the same receiver array. The signals from the surface waves are generated by ambient noise (e.g. traffic) (Figure 5b) and they penetrate deeper than the hammer-generated waves of the active method (Park, Miller, Xia, & Ivanov, 2007). Data were processed using *Seisimager/SW* software. The shear wave velocity profile of the near-surface layers was derived by inversion of the surface wave dispersion curve shown in Figure 6 (Park *et al*., 1999). The latter was extracted from information gathered from both the active and passive acquisition (Figure 6e and 6f). Meanwhile, the compressional wave velocity was computed from the travel time of the direct wave generated by the hammer used to conduct the active method (shot records) and analyzed using the software program *SeisImager/2D*. Seismic tomograms are displayed herein using a fence diagram format by *Sketchup* software.

3.2 Downhole seismic method

The downhole seismic test makes direct measurements of compressional (Vp) and shear wave velocities (Vs) in a single borehole. A seismic source is used to generate a seismic wave train at the ground surface offset horizontally from the top of a cased borehole. The arrival of the seismic waves is detected by downhole geophone. The waves propagate in the direction perpendicular to the source towards the geophone and are

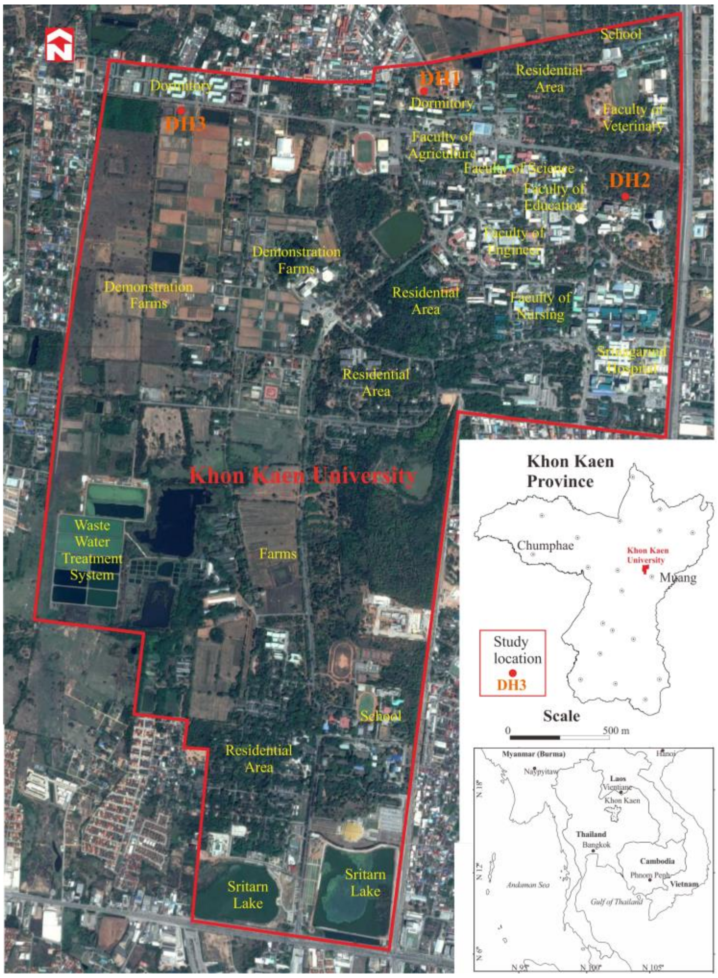

Figure 1. Locations of MASW and downhole tests on KKU campus (image from Google, 2019)

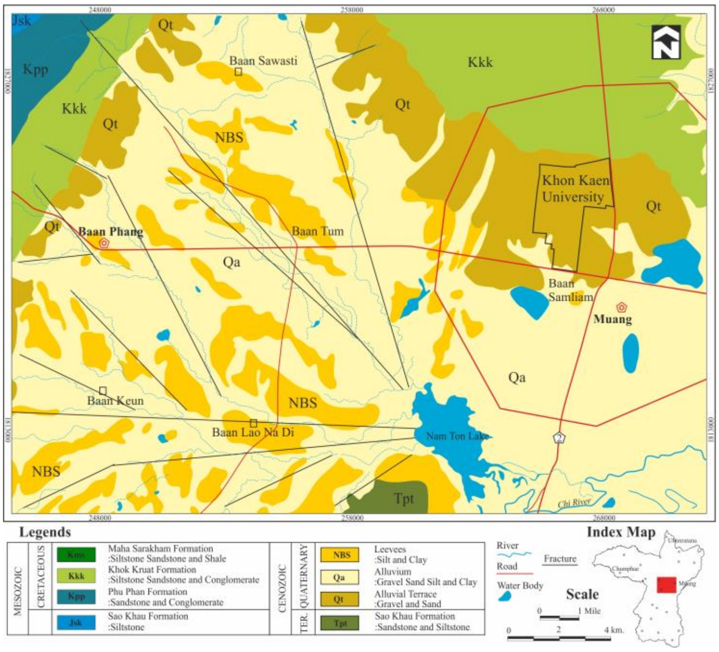

Figure 2. Geological map of Khon Kaen basin (Arjwech, Wanakao, Archwichai, & Wanakao, 2014; Wannakao, Wannakao, Satarugsa, & Arcwichai, 2001).

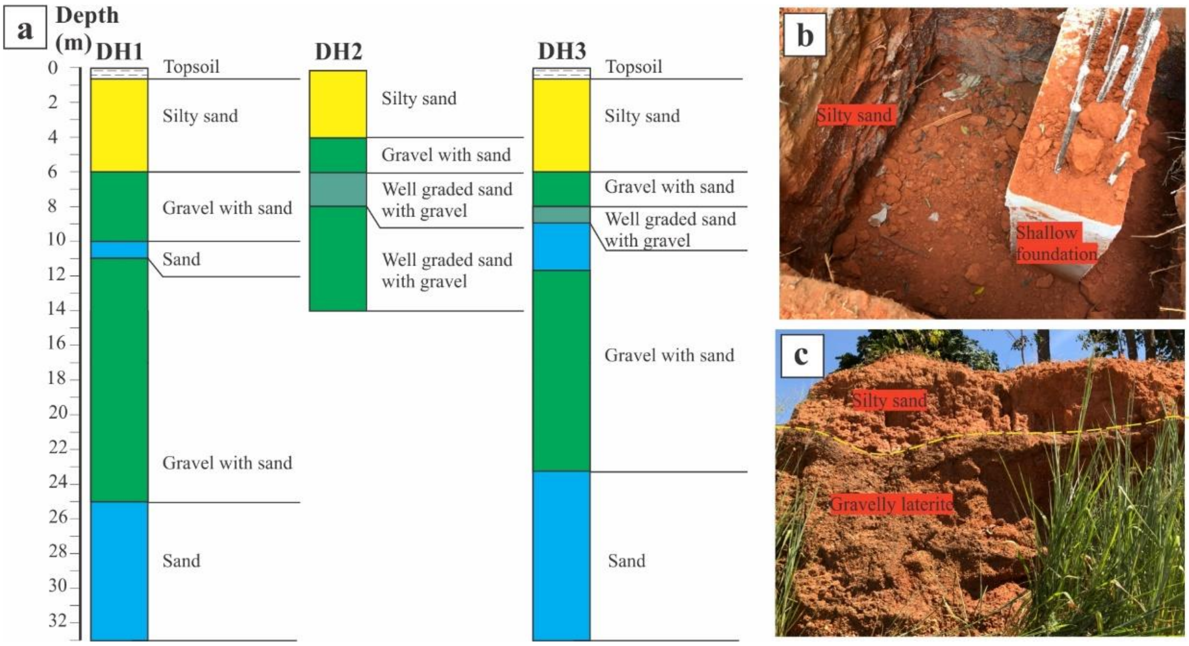

Figure 3. Borehole lithology of DH1, DH2, and DH3, (a) building of shallow foundation in loess soil (b) and gravel layer overlain by silty sand layer well exposed on Khon Kaen University campus (c).

Figure 4. Operation of downhole and MASW techniques, (a-c) borehole drilling and set up, (d) downhole testing, (e) active MASW data acquisition at BH1, and (f) passive MASW data acquisition at BH2

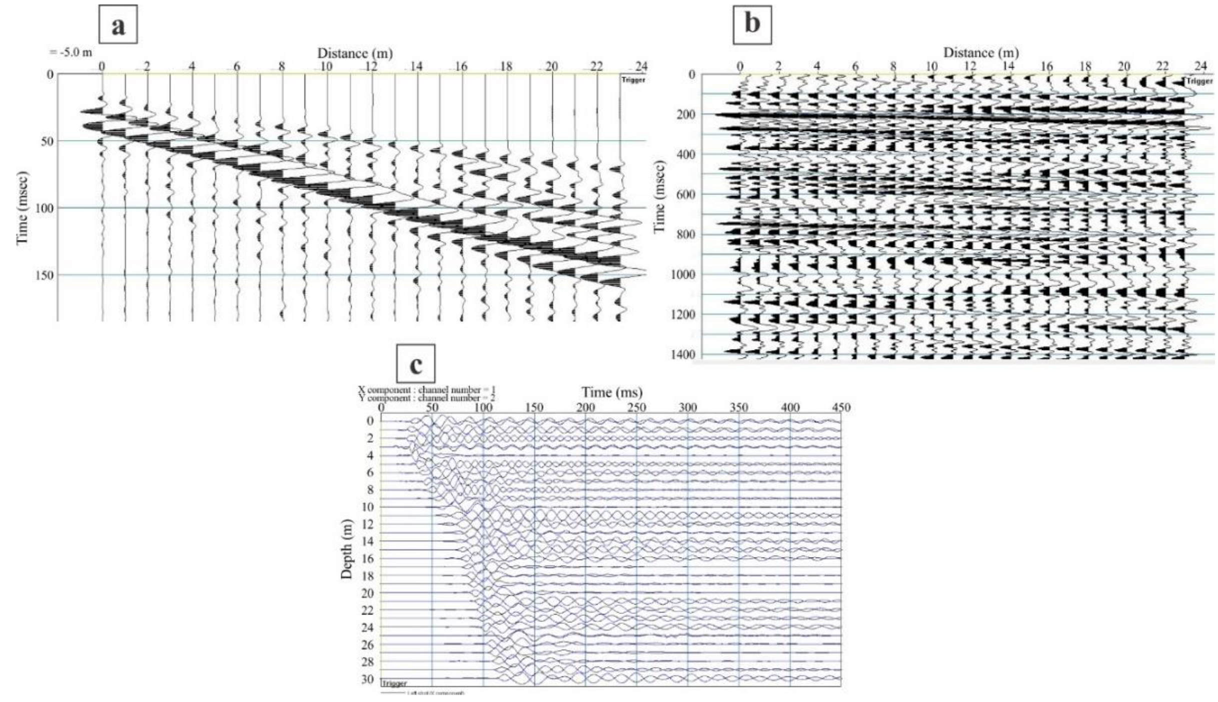

Figure 5. Sample data of BH1; shot gathers from active (b) and passive (c) surveys and two opposite polarities of shear-wave fields from downhole seismic surveys (a)

recorded at various locations and signals are displayed on a seismograph (Aizawa, 2014).

For the downhole test, a seismic wave was again established using a sledge hammer. The compressional wave was generated by vertical impact onto a metal strike plate. The shear wave was generated by horizontal impact onto both ends of the wooden plank weighted down with a vehicle. It generated two opposite polarity shear-wave fields shown in Figure 5c. Wave signals were collected every 1 m depth using a tri-axial receiver geophone attached to the wall of the borehole. The shear and compressional wave velocities were calculated using the observed one-way travel time from the seismic source to the receiver geophone. Data were processed using *Win-Downhole* software.

When Vp and Vs are known, the determination of elastic properties of loess soils can be calculated from the seismic velocities. So, Poisson's ratio (n_p) can also be determined from the following equation;

$$v_p = ((Vp/Vs)^2-2)/ (2(Vp/Vs)^2-1) \quad (1)$$

where Vs is the shear wave velocity and Vp is the compression wave velocity.

Shear modulus (G) can be determined according to the following equation:

$$G = dVs^2 \quad (2)$$

where d is bulk density of the ground. Natural dry density of loess soil (1,500 kg/m^3) on campus of Khon Kaen University is studied by Chong (1988).

Accordingly, dynamic Young's modulus (E) can be estimated as follows:

$$E = 2G(1+F_p). \quad (3)$$

Bulk modulus (K) can be calculated from the following equation:

$$K = 1/3(E/(1-2F_p)). \quad (4)$$

4. Results and Discussion

The MASW results from the three sites DH1, DH2 and DH3 are respectively shown in Figures 7a–9a. They consist of 2D cross-sections in which the horizontal distance appears on the horizontal axis and depth appears on the vertical axis. The downhole results are shown in Figures 7b–9b as depth profiles of compressional and shear velocity. Based on the geological stratigraphy obtained from borehole logging, and the shear wave velocity contrasts evident in the depth profiles, the shear wave velocity of the surficial loess layer shows the lowest values in the MASW cross-sections (displayed in blue color). The underlying zone displayed in the green color is interpreted as a ravel layer and dense sand layer characterized by a higher shear wave velocity. The zones of highest shear wave velocity are displayed in reddish-brown to red colors. Such zones are located near the bottoms of the MASW cross-sections in Figures 8 and 9; they are interpreted as semi-consolidated sediment or weathered rock.

Results from the three sites are summarized in Table 1. The shear wave velocity of the surficial loess obtained using the MASW method varies from 242 to 329 m/s. The compressional wave velocity of this layer ranges between 371 and 740 m/s. The elastic moduli deduced from MASW data show that the loess shear modulus ranges between 93.7 and

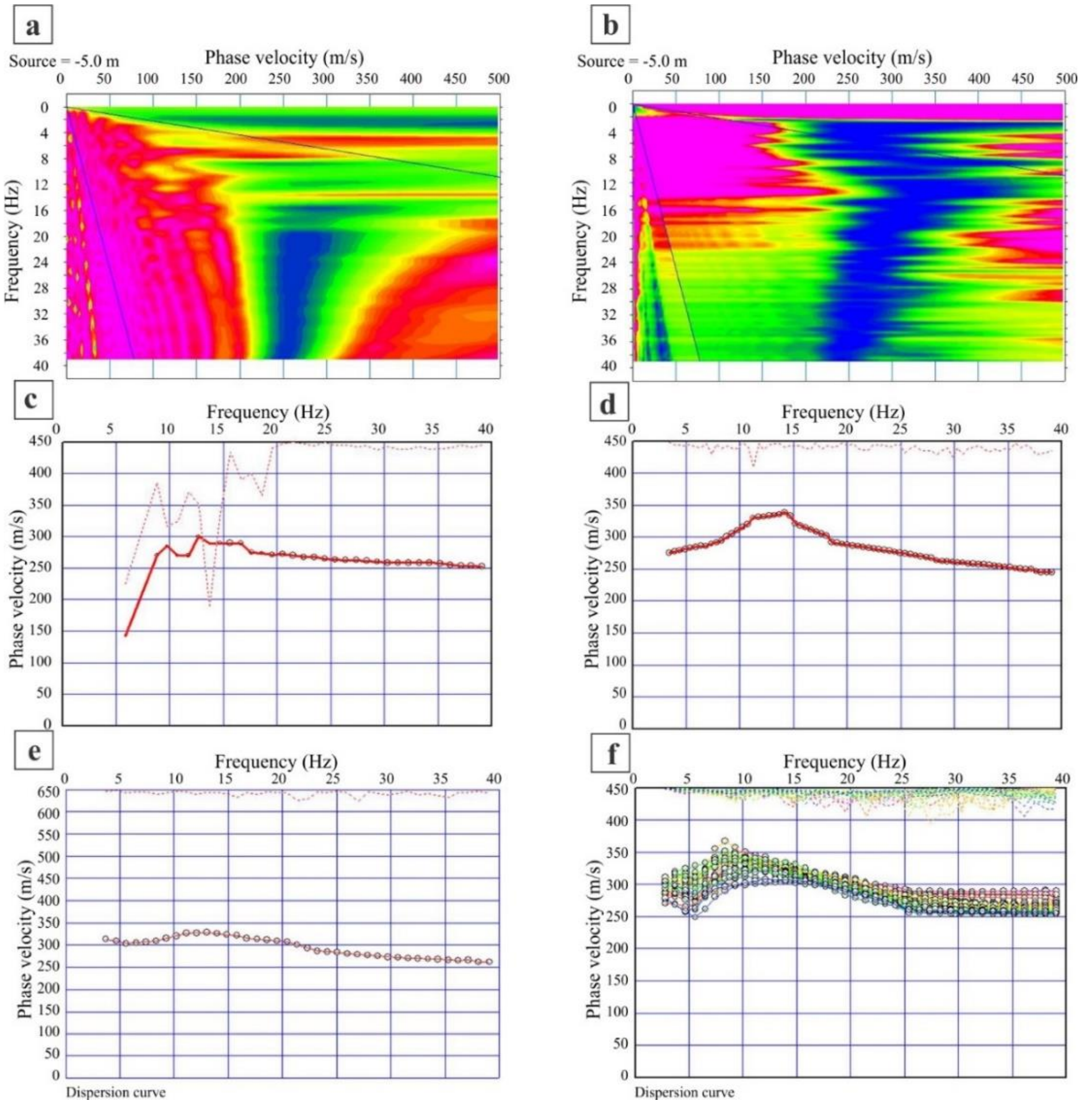

Figure 6. Dispersion images of borehole BH1 obtained from active (a) and passive (b) MASW surveys, inversion of dispersion curve from active (c) and passive surveys (d), two sets of image (a and b) data are combined to enlarge the frequency range of dispersion (e), combination of dispersion curves for 2D image

173.2 MPa while a range from 58 to 687 MPa is found for the bulk modulus of the loess. The body wave velocities obtained from the downhole seismic method indicate a range from 210 to 323 m/s for the shear wave velocity of loess while the compressional wave velocity ranges between 420 and 771 m/s. The loess thickness is between 4 to 6 m. The elastic moduli derived from the downhole test show that the loess shear modulus ranges between 70.6 and 166.9 MPa while the bulk modulus ranges from 188.2 to 728.5 MPa.

The loess shear wave velocity and the loess compressional wave velocity derived from MASW method are comparable to the same parameters derived from the downhole seismic technique. It is found that the shear wave velocities show 2-23% differences while the compressional wave velocities show 2-25% differences. Young’s modulus from MASW is between 211.7 and 441.0 MPa and from downhole survey is between 188.2 and 465.3 MPa. However, Young’s modulus determined from MASW is in the range that determined by downhole method. Also, Young's modulus calculated from this study compares with results reported elsewhere; Young's modulus is between 19.6 and 83.2 MPa studied in different moisture condition by Sinchai (2002) and Phien-wej *et al*. (1992) that obtained on Khon Kaen University campus from standard geotechnical engineering tests. It is observed that the values of Young's modulus determined via dynamic geophysics tests are larger than (5 to 20 time approximately) those of determining via static geotechnical tests.

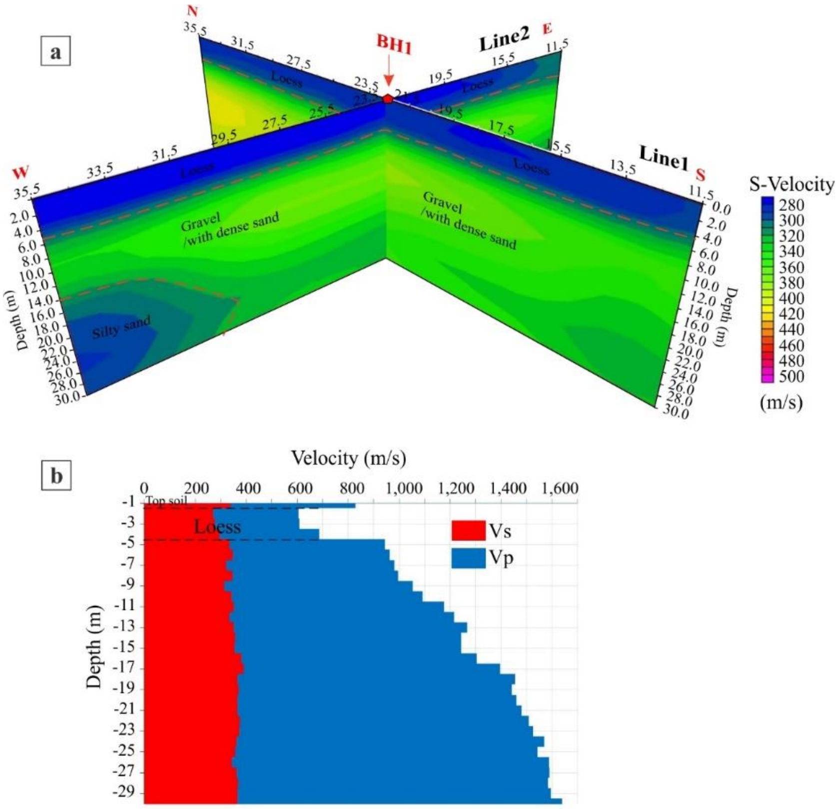

Figure 7. 2D Vs map of BH1 was obtained from a combined analysis of active and passive MASW surveys (a) and the downhole result (b) of BH1

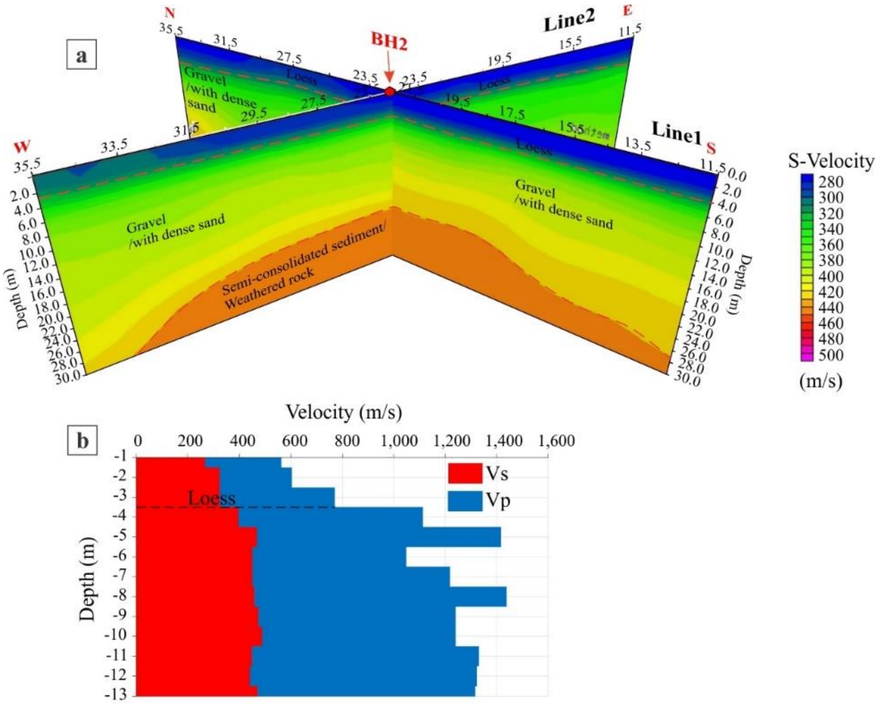

Figure 8. 2D Vs map of BH2 was obtained from a combined analysis of active and passive MASW surveys (a) and the downhole result (b) of BH2

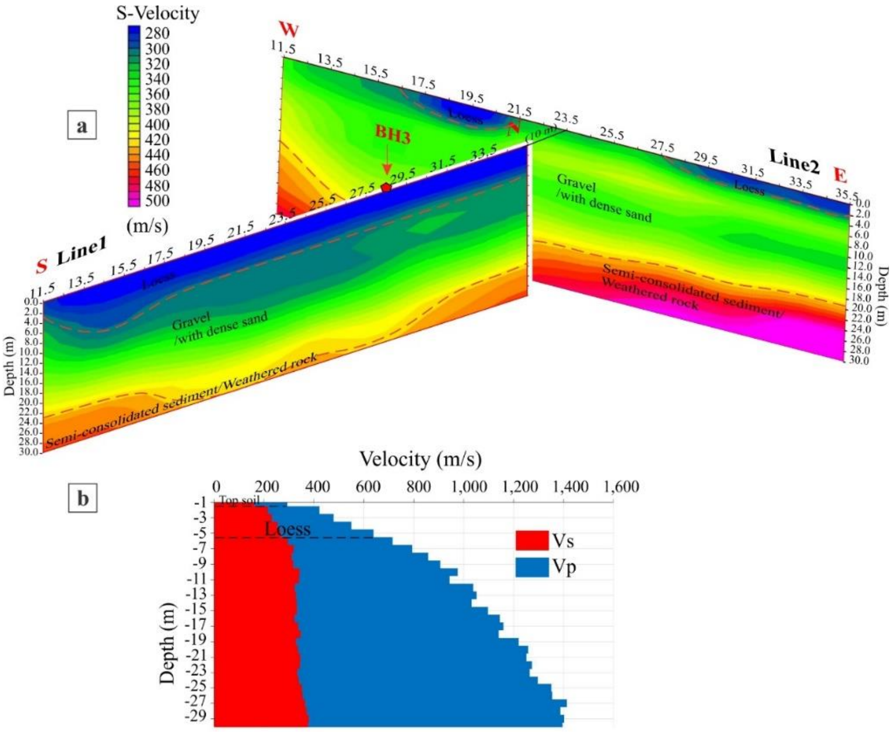

Figure 9. 2D Vs map of BH3 was obtained from a combined analysis of active and passive MASW surveys (a) and the downhole result (b) of BH3

Table 1. Summary of velocity and loess elastic properties derived from MASW and downhole methods.

Velocity/ Property Borehole/ Test				Velocity (m/s)		Elastic property			
				Vs	Vp	Poisson's ratio	Shear modulus (MPa)	Young's modulus (MPa)	Bulk modulus (MPa)
DH 1	Downhole		Min	269	605	0.38	115.78	318.80	431.27
			Max	295	687	0.39	139.24	386.24	569.50
	MASW	Line1	Min	276	450	0.20	121.88	292.15	161.49
			Max	312	686	0.37	155.75	426.63	545.29
		Line2	Min	260	439	0.23	108.16	266.04	164.14
			Max	309	516	0.22	152.77	372.89	222.32
DH 2	Downhole		Min	267	564	0.36	114.06	309.24	356.87
			Max	323	771	0.39	166.93	465.25	728.54
	MASW	Line1	Min	242	371	0.13	93.70	211.71	95.29
			Max	318	531	0.22	161.80	394.92	235.41
		Line2	Min	249	419	0.23	99.20	243.44	148.63
			Max	298	740	0.40	142.09	398.76	686.71
DH 3	Downhole		Min	210	420	0.33	70.56	188.16	188.16
			Max	295	715	0.40	139.24	389.15	632.31
	MASW	Line1	Min	246	450	0.29	96.83	249.21	194.90
			Max	329	589	0.27	173.19	441.02	324.16
		Line2	Min	259	485	0.30	107.33	279.17	233.25
			Max	329	522	0.17	173.19	405.42	205.06

Downhole and crosshole seismic tests are popular geophysics methods for determining engineering properties of subsurface materials. However, they are classified as destructive methods that borehole is required for these tests. Therefore, the Vs wave velocity maps (Vs vs. depth) derived from MASW survey were compared to Vs wave velocity profiles measured in boreholes. An overall difference is lesser than 25%. The MASW survey from this study can provide reliable Vs wave velocity profiles. The accuracy of Vs profle obtained by MASW technique primarily depends upon the resolution of the dispersion curve. Therefore, cross survey lines and 2D survey are required to develop standard guidelines for data acquisition. The MASW can be considered as an alternative method for determining soil elastic properties.

5. Conclusions and Recommendations

The MASW method is a rapid, wide-area non-invasive and cost-effective geophysical method for evaluating engineering properties of loess soil. The elastic moduli can be computed from the shear wave and the compressional wave velocities obtained from the MASW inversion process. The body-wave velocities derived using the MASW method varies from the velocities obtained using the downhole method by roughly 25%. Correlating the velocity profiles from both methods shows that the velocity values compare fairly well and demonstrate that the MASW is a reliable and acceptable method to measure shear wave velocity of the subsurface materials.

Comparing the results using the geophysics approach with previous geotechnical test results from the study area shows 10 to 20 times difference in values. The MASW is a non-invasive surface geophysical technique with the advantage over the borehole measurements. Although the MASW cannot replace the conventional drilling method in determining soil elastic properties, its advantages are such that it can be considered as an alternative method.

This study was carried out in summer season when soil seemed to appear low moisture content. It is suggested that geophysics tests in other seasons are recommended since moisture can effect on engineering properties of soil. For a given project, the dynamic geophysics test should be calibrated by at least one static test.

Density and velocity are important parameter for calculating elastic properties of soil that can be obtained from geophysics and laboratory tests. For MASW survey, compressional wave can be determined directly from active survey data that can process using refraction technique.

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