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Site Characterization of Marine Clay Deposits in South Seberang Prai, Penang using Combined Active and Passive Multichannel Analysis of Surface Wave (MASW)

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Abstract. The multichannel analysis of surface wave (MASW) has drawn considerable interest in subsoil investigation and characterization. This method has been studied and improved in the last few decades, thereby leading to several combinations of existing active and passive methods. This study aims to identify the presence of marine clay layer using combined active and passive MASW methods. The shear wave velocity profile obtained interpreting clay layer within the range of 70–150 m/s and sand layer within the range of 100–300 m/s. Results suggest that the combined MASW method significantly improves shear wave velocity profiling in shallow and deep soil layers and the results are validated using the cone resistance and shear wave velocity estimated from cone penetration test.Introduction

Keywords: Surface wave, passive and active MASW, marine clay.

1. Introduction

Construction over soft clay areas has increased in recent years because of the growth progress occurring in Malaysia. Many potential residential areas, such as Nibong Tebal, aim to be developed. The main concern in designing structures in such areas is identifying the presence of the clay layer and the extent of its depth by conducting costly and time consuming site investigation such as multiple points of close boreholes. Throughout the decades, bore logging has been a common method used to investigate and characterize subsoil conditions. However, obtaining samples from a borehole is an invasive method that will disturb sample properties.

Various non-invasive geophysical methods have been developed to investigate and characterize subsurface condition. Previous researchers have found that shear wave velocity could become a fundamental property in evaluating soil perimeters empirically [1,2,3]. In minimal disturbance, in situ geophysical methods have considerable advantages and accuracies over determining shear wave velocity empirically. Previous techniques, such as seismic reflection analysis, continuous surface wave analysis, and spectral analysis of surface wave, were applied before the multichannel analysis of surface wave (MASW) was developed in the mid-1990s. The limitations of individual active and passive MASW methods lead to the development of the combined active and passive MASW method. Some studies reviewed that combine active and passive method may be beneficial to improve resolution of penetration depth [7,8,9].

Reliability of MASW method has been assess with seismic cone penetration test (SCPT) on southeast Missouri in 2006 and Norwegian sites in 2007 [10,11]. The result reasonably agreed well with those obtained from CPT correlation. As cone penetration test (CPT) became popular, the economic value, continuous records and direct numerical values from various sensors incorporated within it credited CPT as the first rational soil profiling method after boring method [12]. This study aims to identify marine clay deposit using combined active and passive MASW method and the results will be validated with shear wave velocity and cone resistance estimated by CPT. This method shall highlight the capability of the combined active and passive MASW method to be used as rapid and cheaper tool for subsurface characterization in a vast area.

2. Sites description

The surveyed sites are shown in Fig. 1. All the sites are located within a 1.2 km2 radius of the Engineering Campus of Universiti Sains Malaysia, which is located along the west coast of Peninsular Malaysia in the Nibong Tebal, South Seberang Prai, Penang. Active and passive MASW measurements together with the CPT were conducted on eight sites as shown in Fig 1(b).

(a)

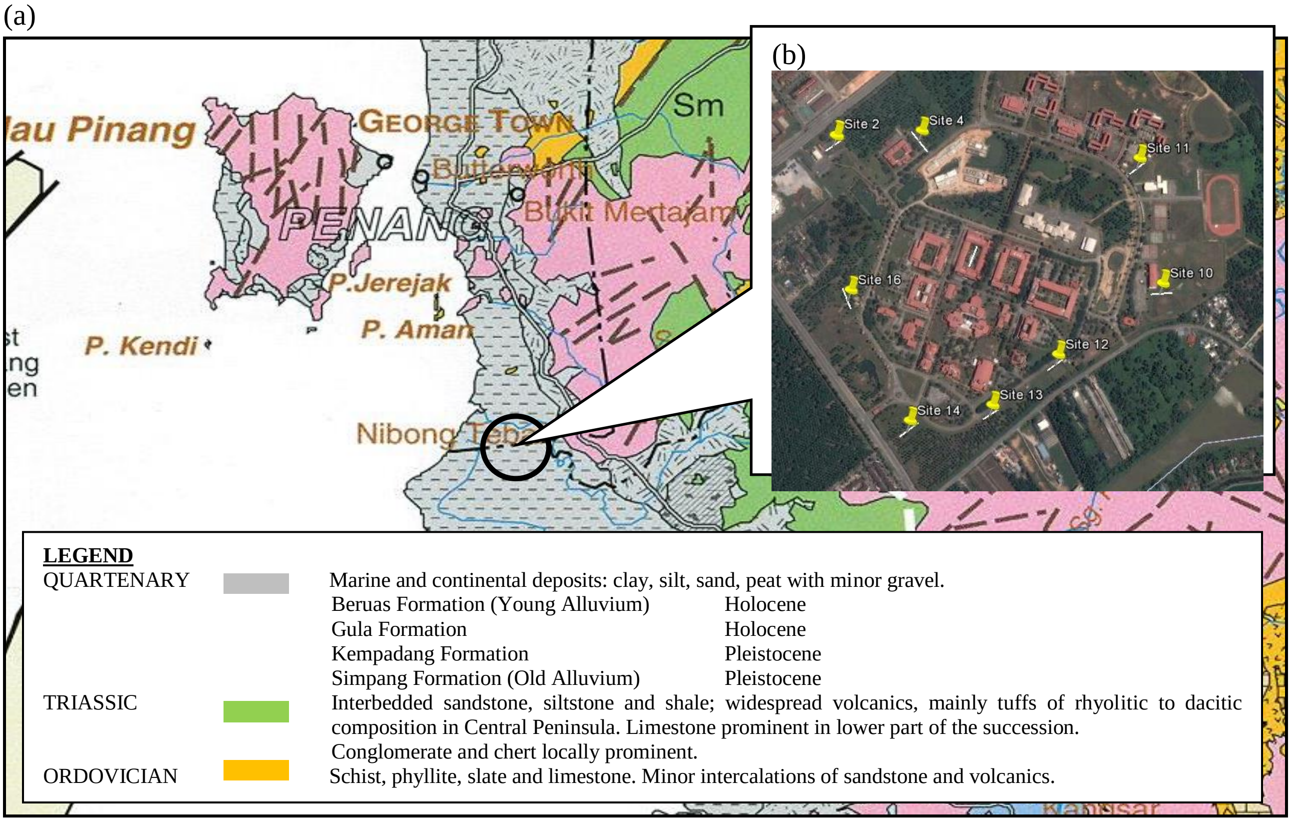

Figure 1. (a) Research location are shown in the Geological Map of Peninsular Malaysia (Geological Department of Malaysia, 1985) and (b) Location of the eight MASW sites.

According to the geological map of Peninsular Malaysia (Fig 1a), the soil along the west coast of Peninsular Malaysia consists of marine and continental deposits such as clay, silt, sand, and peat with minor gravel content. The research area which located within the boundary of Penang and Perak States was previously a mangrove area. Based on the quaternary geology report, the research area belongs to Gula Formation. The lithology of the Gula Formation is described as sand, silt, clay, gravel, and a small amount of peat. Sediments were fluvially deposited in estuaries and littoral zones, which shallower decades ago [13].

3. Methodology

MASW method were divided into passive and active method. As each method has limitation and advantage, combining both method will create an improved MASW version. In this study, MASW sites were measured and analyzed based on the steps in Fig. 2 by using SeisImager software. Surface Wave Analysis Wizard module of SeisImager automatically calls on functions such as Pickwin and WaveEq modules through the processing flows of individual active and passive method. Dispersion point are picked in the stable velocity range of phase velocity-frequency domain displayed in color contour. Dispersion curve will be displayed once WaveEq module lunches. This step applied for active and passive method only with exception on the survey geometry set up of each method. Dispersion curve of combined MASW method created by appending the dispersion curve of active and passive method. Next, the initial model of Vs with depth for one-third-wavelength approximation is set up. The software will iterate to converge on the best fit of the initial model with the observed data to create the final Vs curve.

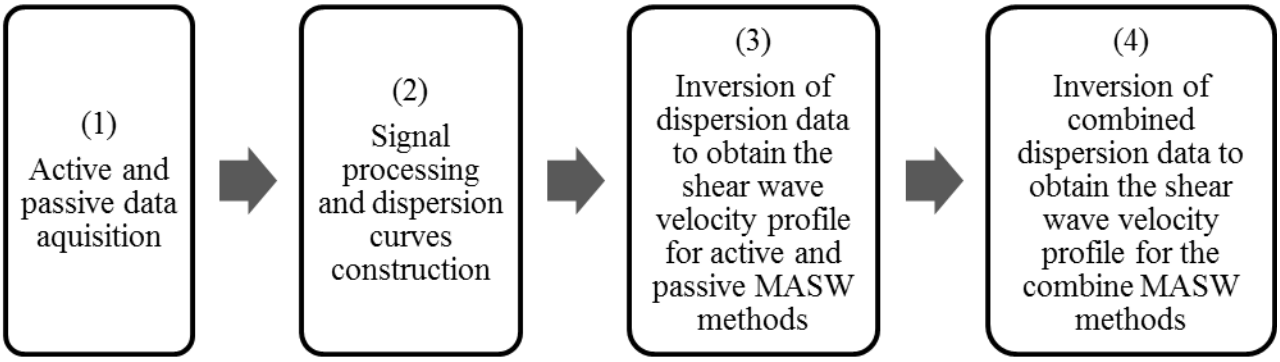

Figure 2. Steps in MASW measurement and analysis using SeisImager software.

Some practitioner are using shear wave velocities as parameter in evaluating soil strength and bearing capacity. This lead to seismic velocities estimation over soils and rock types as in Fig. 3. This study utilize the velocities estimation to estimate the types of soil and rocks from shear wave velocity (Vs) obtained.

Soil and Rock type	V_P m/s	V_S m/s
Gabro	6000	4000
Granite	5640	3760
Schist	5200	3500
Limestone	6190	3350
Mudstone	1900	700
Dilluvial gravel	2200	600
Gravel,dry sand	1000	300
Loose sand	1800	500
Alluvial gravel	1900	430
Diluvial clay	1800	350
Alluvial clay	600	150

Figure 3. The presumptive primary and shear wave velocity [14].

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3.1 Active MASW
The type of seismic activity is categorized based on the type impulse source such as explosion, sledgehammer strike, and many others. In this study, sledgehammer was used. Offset was set at 5, 10, and 15 m from the first geophone with five time stacking to improve signal-to-noise ratio (SNR). This method was adopted from the conventional seismic refraction method. The produced impact would generate surface waves, which would be detected by the geophones. The wave forms shown in the seismogram and dispersion image in the Rayleigh fundamental mode. Shear waves velocity were derived from the inversion of the dispersion curve into a 1D shear wave profile.

3.2 Passive MASW
The passive method based on micro-tremor array measurement (MAM). Passive waves generated by industrial, vehicular, and wind noises were discovered to emit low-frequency wave with greater energy than those emitted by active sources. Researchers found that passive method may overcome the limitation of the active method via deeper wave intrusions. The use of passive waves was introduced when Louie [15] proposed the method in 2001. Common arrays used at present are L, triangles, circles, and semicircles. In this study, “L” arrays were used. A total of 20 records (32s record length each) were used in the study. The dispersion curves were calculated individually for all the 20 records and then stacked together.

3.3 Combined MASW method
Theoretically, high-frequency waves in the active method lack signal information when depth is deep, whereas low-frequency waves in the passive method lack information when depth is shallow. The investigation depth of the active method is less than 30 m, whereas that of the passive method can reach 100 m [4,7,16]. Combined MASW methods resolve the limitations in shallow depth of the active method and the insufficient near-surface signal of the passive method. Passive and active methods are used to measure data individually in sites, and then, the dispersion data from both methods are appended together. The deficiency of each method is improved by smoothening and averaging appended data. The simultaneous active–passive methods combine the dispersion curves generated before inversion to construct a combined MASW shear wave velocity profile. The combined profile covers a better range than both methods individually. Superimposing the dispersion curves obtained from both method create a better quality data.

The general schematic illustration of a multichannel configuration used in the study is shown in Fig. 4. The primary MASW equipment used in the study comprises of 24 geophones (4.5Hz) for active method and 9 geophones (4.5Hz) for passive method. The receiver spacing (2.5m for active and 5m for passive method), represent the shortest generated wavelength, which determines the minimum depth that will be used in the investigation. By contrast, the spread length of the receiver represents the longest wavelength, which determines the maximum depth that will be used in the investigation.

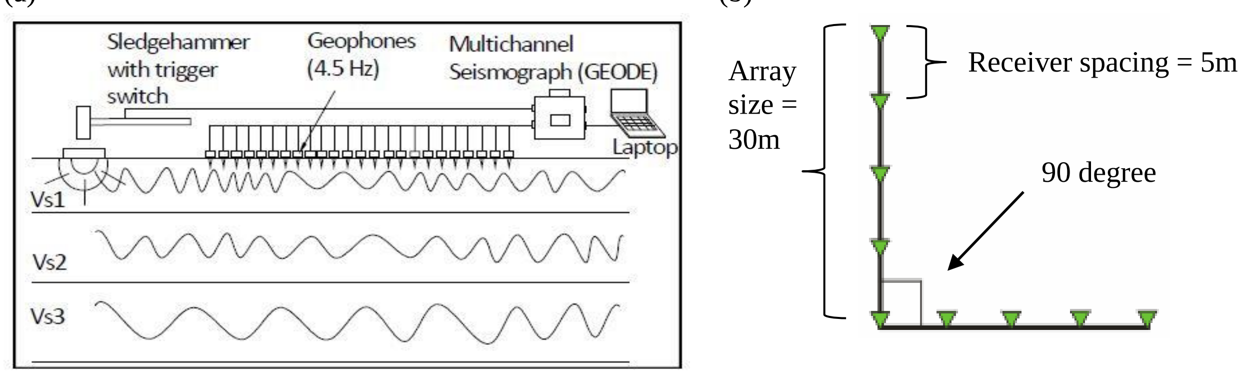

Figure 4. Field configurations of (a) active MASW and (b) passive MASW.

4. Result and discussion

Based on the data obtained from the phase velocity image in the frequency domain (Fig. 5), the frequency range for active method is within 5–25 Hz with phase velocity in 100–150 m/s range and the frequency range for passive MASW was observed to be at 3–14 Hz with phase velocity range in 50–300 m/s. The fundamental modes of the active and passive methods were clearly within the ranges of 3–25 Hz and 2–4 Hz, respectively. The dispersion curve was extracted by selecting minimum frequency of 4.5 Hz for the active method and 3 Hz for the passive method. The shapes of the both dispersion curves are similar, with an apparent bend around 4 Hz. However, the modal curve of passive MASW slightly shifts toward lower phase velocities and produce clear signals in low frequencies. This condition results in the deeper penetration of shear waves compared with the weak signals in the active method. The shear wave velocity profile for the passive method obtained using the inversion method matches well with that for the active method in comparison to its respective depth.

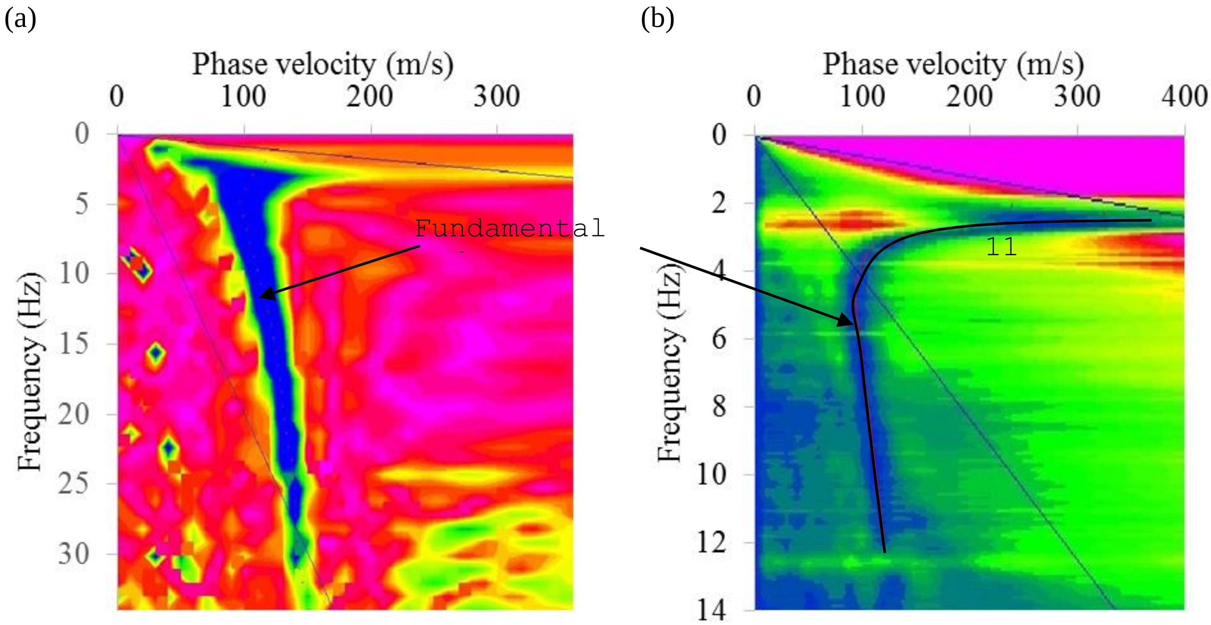

Figure 5. Phase velocity images in the frequency domain for (a) the active MASW method and (b) the passive MASW method.

Fig. 6 shows the data sets obtained using (a) active method, (b) passive method and (c) combination of active and passive methods. The figure shows the shear wave profile obtained after the inversion. The value of the shear wave velocity obtained using the passive method is slightly different from that obtained using the active method (Figs. 6a and 6b) in terms of penetration depth and velocity over depth pattern. Park et al. [7] suggesting combination of dispersion for a reliable modal identification. Vs profile of combine MASW method were improved where, the analyzable frequency range of dispersion broaden and better identification of dispersion trends modal identity. Fig. 6c supporting the facts that combine method is effective for determining shear wave velocity.

According to Tezcan et al. [14], Vs less than 750 m/s is the velocity range for soil. As observe in Fig. 6c, the shear wave velocity of combined active and passive MASW method was observed to be within the range of 50–380 m/s, which confirmed that the study area consist of soil. A clear increase in soil stiffness with increasing velocity is shown in Fig. 6c. Shear wave velocity was observed to decline to 70–150 m/s at a depth of 13 m and increase to 350 m/s up to a depth of 30 m. In 2008, Watabe and Sassa [17] reported that the Vs of soft clay ranged from 80–175 m/s, and that of firm clay ranged from 100–300 m/s, while sand ranged from 130–300 m/s by Xia et al. [18] in 2002. From VS obtained in Fig. 6c, the soil type estimated in the first 13 m was the clay layer, whereas the sand layer located at a depth of 13 m to 40 m.

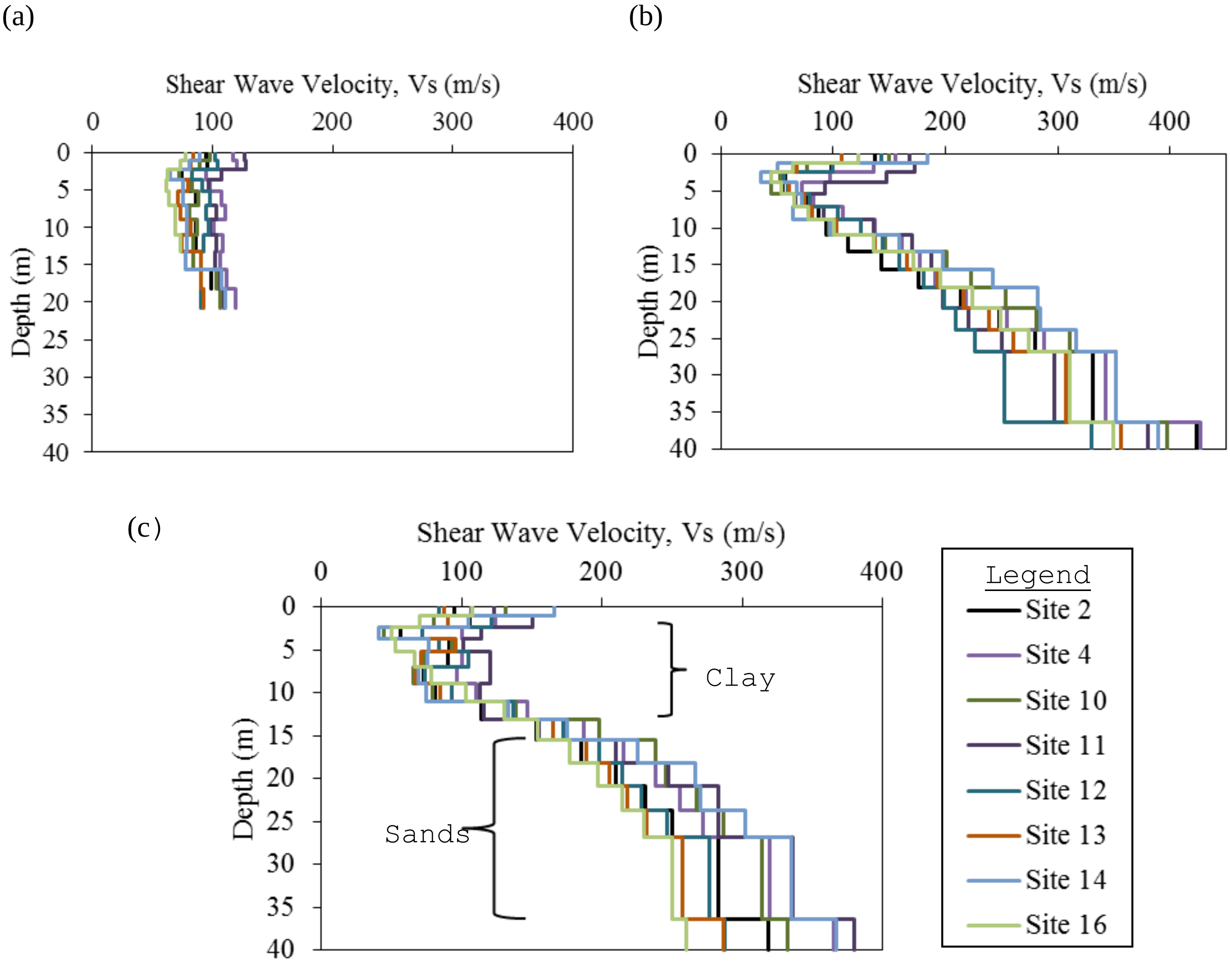

Figure 6. Shear wave velocity profiles of (a) active MASW, (b) passive MASW, and (c) combined MASW method.

A better explanation for combined method was illustrated in Fig. 7a. The three methods, active, passive and combined MASW was in good agreement in the first 13m, however start to diverge after 13 m depth. This may be because of the uncertainties with the low frequency dispersion curves [8]. Fig. 7b shows the shear wave profile overlay with one-third wavelength approximation obtained from the SeisImager software.

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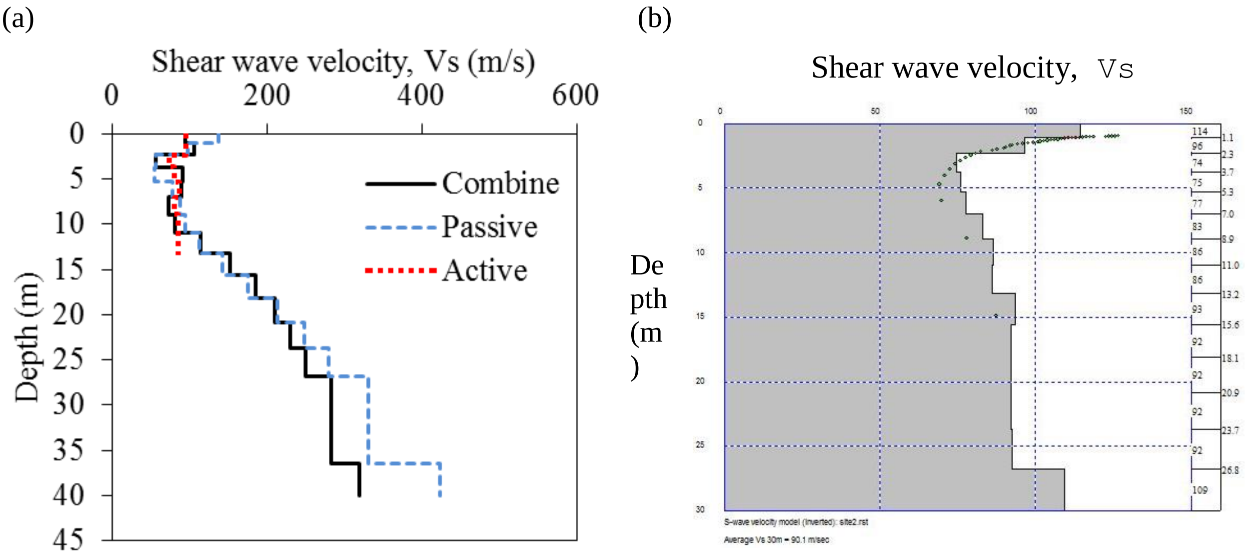

Figure 7. (a) Comparison of shear wave velocity profiles obtained using active, passive, and combined MASW and (b) 1D velocity model represented by actual depth range of penetration in Seismager.

Shear modulus reflect to material stiffness and is one of the most critical engineering parameters. Seismically, shear wave velocity is an important indicator to determine small strain shear modulus of soil as described in the equation below;

$$V_s = \left(\frac{G_o}{\rho} \right)^{0.50} \qquad (1)$$

Where G_o is small strain shear modulus determined using Eq (2) and ρ is the density of the materials.

$$G_o = (q_t - \sigma_v) 0.01888 \times 10^{0.55 I_c + 1.68} \qquad (2)$$

Where q_t is cone resistance; σ_v is vertical overburden stress and I_c is SBTn Index.

Shear wave velocity estimated from CPT using the Eq. (1) and cone resistance show a consistent trend with the shear wave velocity measured using combine MASW as shown in Fig. 8a. The soil type estimation as interpreted in Robertson's Soil Behavior Type (SBT), consist of clay layer in the first 15 meter followed by sand in the next layer (Fig. 8b). The CPT result validate the interpretation and result measured from combine MASW method as described in figure below.

(a) (b)

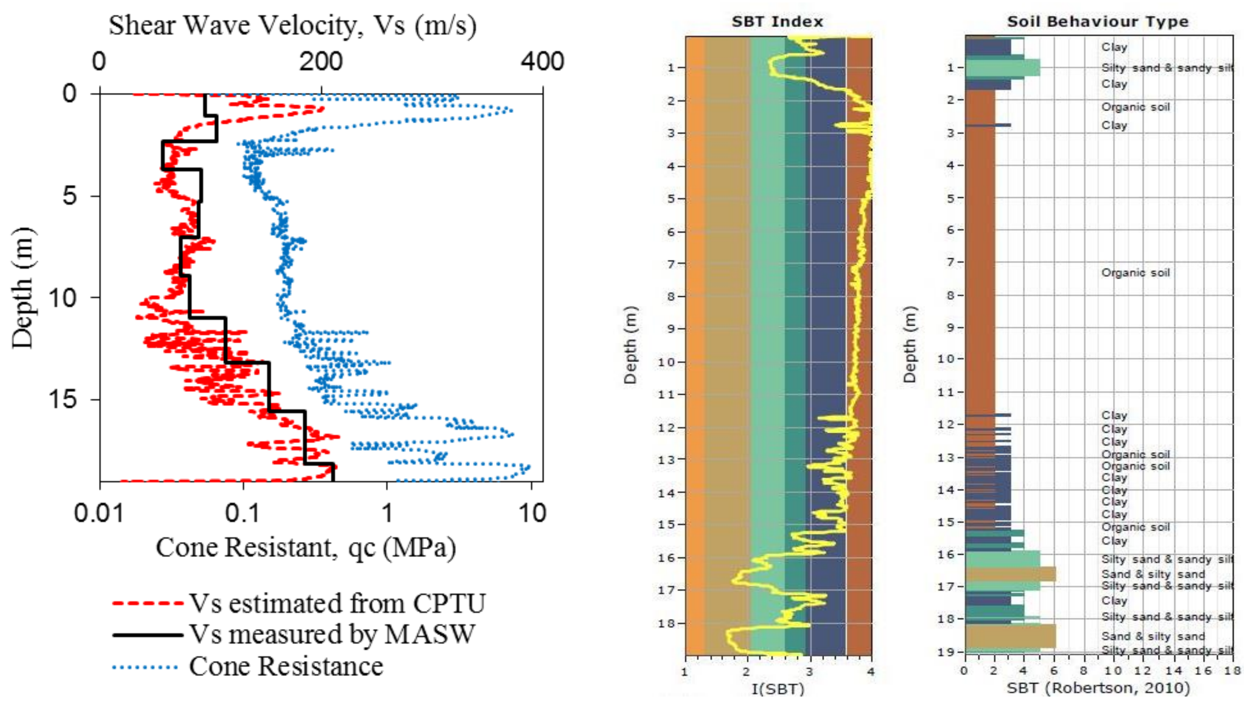

Figure 8. (a) Similar trend of shear wave velocity estimated from CPT and measured using the combined MASW method and (b) CPT estimation in the SBT index.

Conclusion

The measurements of the combined method exhibit a slightly different shear wave velocity from those obtained using the active and passive methods. The active method only covers the near–surface layer, the passive method covers the deep layer, and the combined method provides a better range than both the active and passive methods. The active, passive, and combined methods closely agree with one another in terms of the capability for soil investigation among surface-based methods. The results show that the combined method significantly enhances the capabilities of MASW for deep soil investigation. Moreover, the method is accurate for soil layer investigation, as validated via cone resistance and estimated shear wave velocity calculated empirically from cone penetration test in this study.

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