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Determination of Soil Bearing Capacity from Spectral Analysis of Surface Wave Test, Standard Penetration Test and Mackintosh Probe Test

Sadia Mannan Mitu, Norinah Abd. Rahman, Aizat Mohd Taib, Khairul Anuar Mohd Nayan

Abstract: *Spectral Analysis of Surface Wave (SASW) method is one of soil investigation methods which promotes cost-effective and less time-consuming procedures, apart form of its non-destructive nature. This study aims to determine the soil ultimate bearing capacity obtained from the SASW method by using Ali Keceli's equation for sandy silt soil. The finding in terms of bearing capacity is then compared to the Standard Penetration Test (SPT) and Mackintosh Probe (MP) results. All the tests were conducted at seven different locations. It is found that there is no 1:1 relationship between the bearing capacity obtained from SPT and SASW although the pattern of the trendline is similar. However, the pattern of the trendline captured is not as similar as SPT for MP and SASW. The coefficient of determination (R^2) between SPT and SASW varies from 0.74 to 0.95 and the R^2 between the MP and SASW varies from 0.43 to 0.77. The overall R^2 found for SPT and SASW is 0.87 and 0.74 for MP and SASW in all locations. For the comparison with SPT and MP, SASW is well-correlated with SPT and moderately with MP. From this study, it can be concluded that SASW has the potential to determine the ultimate bearing capacity of soil as an alternative to SPT and MP tests.*

Keywords: *ultimate bearing capacity, geophysical method, shear wave velocity, SASW, standard penetration test, Mackintosh Probe.*

I. INTRODUCTION

In foundation engineering, the soil characterization of compacted soil is important to determine the structure that can withstand the imposed loading, thus, principally indicates a practical and safe design. The soil bearing capacity is one of the parameters which outlines the characterization. Field tests of soil characterization to determine the soil properties are commonly destructive in-nature. Moreover, the procedures are costly and time-consuming, not to mention, also leads to the probability of serious damage to the structural integrity of the foundation. Geophysical methods such as SASW can be used to determine the soil characteristics effectively and inexpensively. In general soil testing methods, the genuine stress condition of the soil is easily disturbed while being handled and transported to the laboratory. Therefore, the original state of soil can be determined by using the geophysical method. The geophysical methods are sometimes useful for the inspection of the constructed buildings [1].

The Spectral-Analysis-of-Surface-Waves (SASW) method is an in-situ, non-destructive and noninvasive seismic method for determining the modulus profiles of geotechnical, pavement, and structural systems. Even though the initial cost is higher than the conventional methods due to the requirement of the specialized equipment, the overall expense of this test is cheaper as it is sensibly rapid and requires lesser manpower than any other test. This method is generally governed by the steady-state Rayleigh method which can be generated by hitting the ground surface with a hammer or vibrator. The steady-state Rayleigh wave travels from one location to another which creates a wavelength to determine the phase velocity. Once the wavelength, λ is captured, the phase velocity, V_{PH} can be determined by using the following equation:

$$V_{PH} = f.\lambda \qquad (1)$$

This process is repeated for a number of frequencies to evaluate the dispersion curve of phase velocity and wavelength. Then, the shear wave velocity is derived from the phase velocity. Since the shear wave velocity (V_S) is about 10 percent greater than the Rayleigh wave velocity (V_R) in a uniform half-space, the shear wave is given as in Equation (2).

$$V_S \cong 1.1V_R \qquad (2)$$

The objective of this study is to determine the ultimate bearing capacity from the shear wave velocity (V_s) profile through the SASW method by using Ali Keceli's equation. The result is then being compared to the bearing capacity obtained from the SASW method with SPT and MP test. In this study, seven SPT tests, MP tests, and SASW tests were carried out at two different sites. Four SPT tests, MP tests, and SASW tests have been conducted at the Faculty of Engineering and Built Environment (FKAB), Universiti Kebangsaan Malaysia (UKM) and another three locations were carried out at a construction site in Sungai Merab, Sepang, Selangor. The four boreholes (BH) of FKAB, UKM named BH-1, BH-2, BH-3, and BH-4 as shown in Figure 1(a) and the three boreholes of Sungai Merab are named as BH-5, BH-6, and BH-7. The locations of the test position are as shown in Figure 1(b).

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The coefficient of determination between the bearing capacity obtained from SPT and SASW, MP and SASW were also measured in this study.

(a)

(b)

Figure 1. Location of the tests (a) Sungai Merab, (b) FKAB, UKM

II. LITERATURE REVIEW

In Malaysia, the SASW method is used to determine various parameters of soil such as damping ratio [2], stiffness [3], [4] and bearing capacity of soil [5]–[7]. Bearing capacity is a key parameter to investigate the condition of the soil while constructing a structure. In the past few years, surface wave methods have been widely used to compare with the conventional techniques in many geotechnical engineering projects due to cost and time effectiveness. These applications include assessment of liquefaction potential, geotechnical verification of compaction and site characterization. The in-situ stiffness for the pavement subgrade structure such as elastic modulus, shear wave velocity and the damping ratio also can be measured with the SASW method [8]. These non-destructive methods are proven efficient in comparison to the conventional invasive mechanical techniques where the shear wave velocity (V_S) is theoretically related to the shear modulus, G_{max}. Equation 3 shows the relationship between the modulus and the shear wave velocity.

$$G_{max} = \rho V_S^2 \qquad (3)$$

It can be noted that G_{max} is the shear modulus (pa), V_S is the shear wave velocity (m s $^{-1}$) and ρ is the density (kg m^{-3}). Rayleigh wave-particle propagates in elliptical paths along the free surface of the earth. For near-surface applications, surface wave methods have exploited Rayleigh waves. To determine the dynamic properties of the subsurface, the surface waves is based on the dispersion of Rayleigh waves. The velocity of the Rayleigh wave is dependent on the frequency. A Rayleigh wave of lower frequency has a relatively long wavelength. the wave with longer wavelength (low frequency) can travel faster than the wave with shorter wavelength (high frequency).

Tan et al. [9] proposed some empirical correlation between V_s and N_{spt} by considering the UBC site classification in the northern region of Malaysia, Penang. The V_s profiles of the ten selected sites were verified through the empirical correlations between V_s and standard penetration resistance of soil proposed by Marto et al.[10]. Bawadi et al. [2] determined shear strain amplitude from the frequency response curve and the damping ratio from time travel data by using the SASW method. In the same year, Ismail et al. [11] implemented the SASW technique to evaluate the thickness profile of subsurface materials but the result showed that it gives better accuracy only for soil but not for the pavement material. Khairul et al. [5] then formulated a theory to determine the ultimate bearing capacity of piles based on the theory of the ultimate bearing capacity of shallow foundation proposed by Keceli et al. [12]. The results were compared with the static pile bearing capacities calculated by using conventional methods proposed by Meyerhof et al. [13] for the SPT-N values and the Schmertmann, Bustamante, and Gianeslli method [14], [15] for the SCPTu values. The performed seismic tests have shown that the shear wave velocity profiles are strongly related to the ultimate pile bearing capacities. The percentage error in the ultimate bearing capacity of the piles between the adapted seismic and the conventional methods for all the sites was found to be -4.77%, -3.01% and -0.93% at Hulu Langat, Mutiara Damansara and Collierville sites respectively.

Ismail et al. [11] also showed that the SASW method can assess the pavement condition. The readings show good comparison with the Heavy Weight Deflectometer (HWD) method for the elastic modulus of soil in Malaysia airport. Moreover, Widodo et al. [7] carried out the dynamic cone penetrometer (DCP) and SASW tests at the same location and found a good correlation between the shear wave velocity and dynamic elastic modulus ($E_{dynamic}$) at Wonosari National Road (Piyungan to Gading) and Prambanan State Road (Prambanan to Pakem), Yogyakarta Province, Indonesia. The empirical model between the shear wave velocities and DCP values were adopted for the subgrade layer by using empirical models proposed by Rosyidi, Nayan & Taha (2004) which were written as Equation (4).

$$DCP = 45{,}668\, V_S^{-1.58} \qquad (4)$$

Where V_S = shear wave velocity (m/s) and DCP is the penetration per mm of an 8 kg drop weight. The hyperbolic stress-strain model of Hardin & Drnevich [16] and the empirical equation proposed by Tezcan et al. [17] were utilized to predict the allowable bearing capacity. Results showed that the average differences between the allowable bearing capacity of shallow foundation calculated from theoretical and V_S based empirical equations with the Macintosh Probe test were consistent.

Tezcan et al. [17] proposed the empirical equation to estimate the allowable bearing capacity of shallow foundation based on more than 373 case studies. They proposed the following equation to determine the allowable bearing capacity from the shear wave velocity of the soil profile.

For hard rocks, $V_S > 4000\ m\ s^{-1},\ n = 1.4$

$$q_a = 0.071\ \gamma V_S \qquad (5)$$

For soft weak rocks, $750\ m\ s^{-1} \le V_S \le 4000\ m\ s^{-1},\ n = 4.6 - 0.0008\ V_S$,

$$q_a = 0.1\ \frac{\gamma V_S}{n} \qquad (6)$$

For soft soils, $750\ m\ s^{-1} \ge V_S,\ n = 4.0$,

$$q_a = 0.025\ \gamma V_S\ \beta \qquad (7)$$

Where, q_a is the allowable bearing capacity (kN m^{-2}), γ is the unit weight (kN m^{-3}) of soil, and V_S is the shear wave velocity measured under the foundation (m s^{-1}), n is the factor of safety and β is the correction factor. Eq. (1) is valid for the soft soils as the shear wave velocity is usually less than 1000 (m s^{-1}).

Keceli et al. [17] used the shear wave velocity for the determination of allowable bearing pressure based on several case studies. The state of stress and the related elastic parameters of a typical soil column are shown in Figure 2.

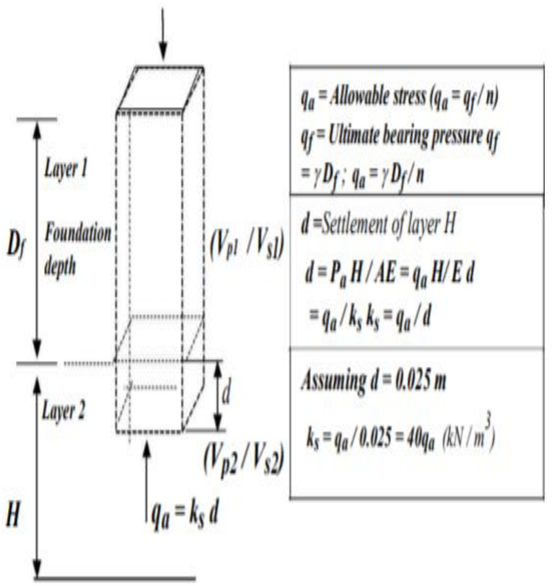

Figure 2. Soil column and related parameters [18]

III. METHODOLOGY

A. Setup configuration

The arrangement of the SASW testing equipment is shown schematically in Figure 3. This method is nondestructive as no borehole is required. The hammer is used as a source to hit the ground which generates a group of surface waves with various frequencies. The source and receivers are placed on the ground surface. The receivers are placed in 1 meter apart and source distance was changed at 1 m, 2 m, 4 m, 6 m, 8 m accordingly. Several factors were considered in the receiver geometry. To avoid near field effects associated with Rayleigh waves and body waves, the distance from the source to the receiver is at least, half of the maximum recorded wavelength. After hitting the ground by source, the phase velocity dispersion curve was analyzed from the phase of the cross-power spectrum between the two receivers.

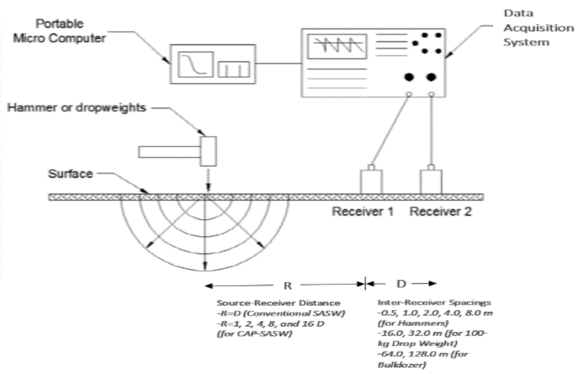

Figure 3. Field arrangement of SASW test [19]

Spectral analysis, via the Fourier transform, can convert any time-domain function into its frequency domain. The cross-power spectrum yields two valuable outputs from the simultaneous spectral analysis of time-domain functions. One output is the phase difference between the time domain functions as a function of frequency. The difference spectrum of this phase can be converted to a time difference (as a function of frequency) by using Equation 8:

$$\Delta t(f) = \frac{\phi(f)}{2\pi f} \qquad (8)$$

Where, Δt (f) = frequency-dependent time difference, Φ (f) = cross-spectral phase at frequency f, F = frequency to which the time difference applies. If the two-time functions analyzed are the seismic signals recorded at two geophones at a distance D apart, then the velocity, as a function of frequency, is given by Equation 9:

$$V(f) = \frac{D}{t(f)} \qquad (9)$$

Where, D = distance between geophones, $t(f)$ = term determined from the cross-spectral phase. n. The wavelength (λ) can be measured by Equation 10:

$$\lambda(f) = \frac{V(f)}{f} \qquad (10)$$

The shear wave velocity profile is then obtained through inversion or forward modeling from the dispersion curve.

B. Theory of the proposed method

According to Keceli et al. [12], seismic impedance (Z) given as its density multiplied by shear wave velocity is related to the bearing capacity of soils. Also, it has been shown theoretically that the imaginary and the real component of seismic shear wave impedance represent cohesive resistance and internal frictional resistance, respectively. As such, the bearing capacity equation for a shallow foundation based on the impedance value of soils irrespective of its depth is given by:

$$Z = \rho . V_S \qquad (11)$$

Where ρ is the mass density and V_S is the shear wave velocity.

In this situation, the weight of the ground above the base level of the foundation is replaced by an equivalent load as shown in Figure 3. The equivalent load or the overburden pressure at foundation level, q_f, is normally expressed as:

$$q_f = \gamma . d_f \qquad (12)$$

Where γ is the unit weight of the soil and d_f is the depth to the bottom surface of the foundation.

If the overburden stress of soil of depth z as shown in Figure 4 is the critical pressure to cause bearing capacity failure, it can be considered as the ultimate bearing capacity of the soil under a foundation. In this case, the pressure at the bottom of the soil column with the unit cross-sectional area becomes:

$$q_z = q_u = \gamma_z = g.\gamma.z \qquad (13)$$

Where q_z is the pressure of the soil column, q_u is the ultimate bearing capacity, g is the acceleration of gravity, ρ is the mass density and z is the depth of the soil column.

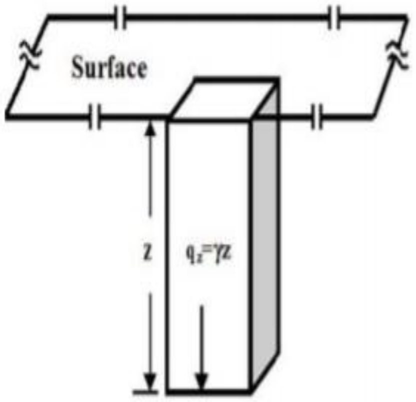

Figure 4. The soil column to cause bearing capacity failure [12]

To evaluate ultimate bearing capacity, the value of z in Equation (13), is substituted with the product of V_S and T and the equation is then transforming into:

$$q_u = g.\gamma.V_S.T \qquad (14)$$

In terms of allowable bearing capacity:

$$q_a = \frac{q_u}{1.5} \qquad (15)$$

From standard values of the allowable bearing capacity of the hardest rock of V_S = 4000 m/s, γ = 35 kN/m^3 and qa = 10 MPa, Equation (14) can be simplified to the following expression to obtain the ultimate bearing capacity of shallow foundation, given by:

$$q_u = 0.1.\gamma.V_S \qquad (16)$$

From Equation (15), the unit weight of soil is obtained from its mass density by using Keceli`s formula 3 (Keceli, 2012) as given in Equation (16). This equation is based on experimental shear wave values given by:

$$\rho = 0.44\, V_S^{0.25} \qquad (17)$$

In this study, Equation (16) is assumed to determine the ultimate bearing capacity of the soil.

IV. Result and Discussion

After obtaining the bearing capacity from SASW, SPT and MP tests, the comparison of the bearing capacity were performed as described in this section. As mentioned before, the input of dynamic analysis depends mainly on the dynamic soil properties that can be determined through shear wave velocity. In this study, the SPT test was done in 2014 and after several years it is assumed that the soil experienced settlement, overburden pressure and weathering process that affected the strength of the soil.

In this study, the empirical relationship between the SPT and MP with SASW was analyzed. The value of R^2 between both the SPT and MP with SASW for all boreholes was shown in table 1.

Table 1. The relationship between SPT and MP with SASW for all boreholes

Borehole no.	R^2 (SPT vs SASW)	R^2 (MP vs SASW)
BH-2	0.95	-
BH-3	0.74	0.43
BH-4	-	0.56
BH-5	0.81	0.58
BH-6	0.91	0.65
BH-7	-	0.77
All boreholes	0.87	0.74

Figure 5 shows the empirical relationship between the SPT and SASW for BH- 2, BH- 3, BH- 5 and BH- 6. BH- 2 and BH- 6 show a significant relationship between SPT and SASW where R^2 is 0.95 and 0.91 respectively. From table 1, it can be seen that the R^2 is 0.74 for BH- 3 and 0.81 for BH- 5. It is reported that there was a reading error while conducting the SASW experiment at BH3 because the high shear wave value was recorded during field tests. Since the geophones were not placed horizontal and stable when this test was carried out, thus, increasing the reading of the shear wave velocity value. Another reason is that the value from SASW at BH3 varies from 350 to 500, found to be not widespread, and the other borehole varies from 200 to 700. The R^2 could be much better if a few more points can be found at the BH-3.

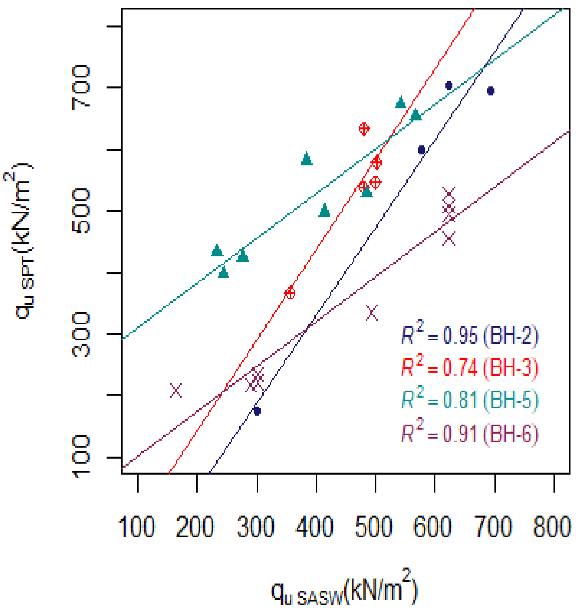

Figure 5. Correlation between SPT and SASW for BH2, BH3, BH5, BH6

The empirical relationship between the MP and SASW for BH-3, BH-4, BH-5, BH-6, and BH-7 is shown in Figure 6. Although SASW does not have a considerable co-relationship with the MP as SPT, the R^2 varies from 0.43 to 0.77 which can be considered moderately correlated. By analyzing Figure 6, the value varies from 200 to 500 for BH-3, 200 to 350 for BH- 4, 450 to 700 for BH- 5, 150 to 600 for BH- 6 and 300 to 600 for BH- 7.

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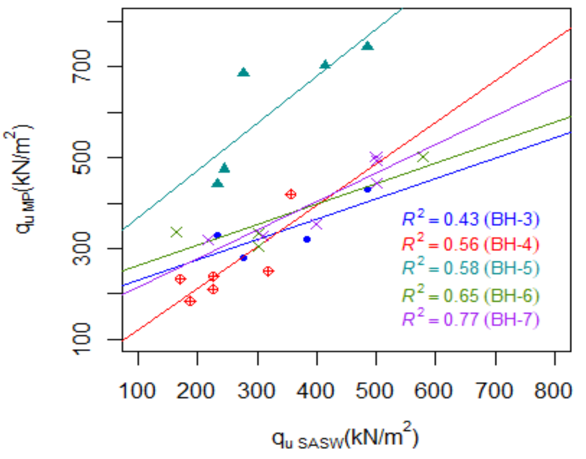

Figure 6. Correlation between MP and SASW for BH-3, BH-4, BH-5, BH-6, and BH-7

Nayan et al. [5] compared the ultimate pile bearing capacity between the SPT and SASW method and found the average percentage error -2.90%. But in this study, the overall percentage error was found -8.5% between the soil bearing capacity obtained from SPT and SASW techniques for seven boreholes. Figure 7 depicts a strong and positive association between SPT and SASW for all boreholes. The R^2 is 0.87 which indicates a strong correlation between SPT and SASW as shown in table 1. There is an offset between the bearing capacity from SPT and SASW, but this offset can be measured of different soil to calibrate the SASW method in future studies.

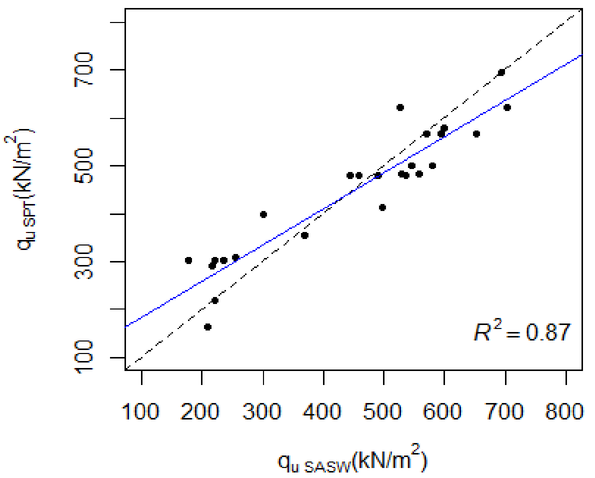

Figure 7. Correlation between SPT and SASW for all boreholes

The R^2 between MP and SASW is 0.74 which is also acceptable (see Figure 8). The correlation coefficient greater than 0.7 indicates a strong positive relationship. Since the sphere of influence of SASW is slightly high rather than SPT and MP, therefore, SASW provides a higher resolution or better condition of the soil. It can be said that there is a difference in the measurements between the tests. The type of soil for all the boreholes are given in Table 2.

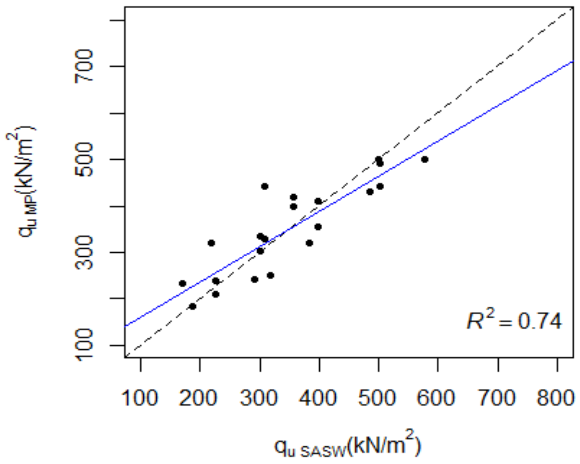

Figure 8. Correlation between MP and SASW for all boreholes

The trendline of the bearing capacity obtained from SPT, MP, SASW was discussed below. Table 2 shows the type of soil for all boreholes.

Table 2. Soil type for all boreholes

Depth	BH-1	BH-2	BH-3	BH-4	BH-5	BH-6	BH-7
1.5	Firm Reddish Brown Sandy Silt	Firm Yellowish Brow Sandy Silt	Loose Brownish Grey Sand	Hard Yellowish-Brown Sandy Silt	Stiff Medium Yellow Sandy Silt	Firm Light Brown Sandy Silt	Firm Medium Brown Sandy Silt
3	Firm Yellowish-Brown Sandy Silt	Firm Reddish Brown Sandy Silt	Hard Light-Yellow Sandy Silt	Hard Brownish Grey Slightly Grovelly Sandy Silt	Very Stiff Medium Grey Sandy Silt	Firm Medium Brown Sandy Silt	Stiff Medium Brown with Yellow Sandy Silt
4.5	Stiff Yellowish-Brown Sandy Silt	Hard Light Yellow Molled Slightly Grovelly Sandy Silt	Hard Light-Yellow Sandy Silt	Hard Yellowish-Brown Sandy Silt	Hard Light Grey Sandy Silt of Low Plasticity	Stiff Light Grey Sandy Silt	Stiff Light Brown with Yellow Sandy Silt
6	Hard Yellowish-Brown Sandy Silt	Hard Yellowish-Brown Sandy Silt	Hard Light-Yellow Sandy Silt	Hard Yellowish Grey Sandy Silt	Hard Medium Yellow Sandy Silt	Stiff Medium Yellow Sandy Silt	Stiff Medium Brown with Yellow Sandy Silt
7.5	Hard Yellowish-Brown Sandy Silt	Hard Yellowish Grey Silt	Hard Light-Yellow Sandy Silt	Hard Yellowish Grey Slightly Grovelly Silt	Hard Yellow Sandy Silt	Very Stiff Light Brown Sandy Silt	Stiff Yellow Sandy Silt
9	Hard Brownish Grey Sandy Silt	Hard Yellowish Grey Silt	Hard Light-Yellow Sandy Silt	Hard Yellowish Grey Slightly Grovelly Silt	Hard Medium Brown Sandy Silt	Very Stiff Medium Brown with Yellow Sandy Silt	Very Stiff Yellow Sandy Silt
10.5	Hard Brownish Grey Sandy Silt	-	-	Hard Yellowish Grey Slightly Grovelly Silt	Hard Medium Brown Sandy Silt	Very Stiff Medium Red Sandy Silt	Very Stiff Light Brown Sandy Silt of Interm ediate Plasticity
12	Hard Brownish Grey Sandy Silt	-	-	Hard Yellowish Grey Slightly Grovelly Silt	Hard Pale Grey Sandy Silt	Hard Medium Red Sandy Silt	Very Dense Medium Grey Silty Sand
13.5	-	-	-	-	Hard Light Grey Sandy Silt	Hard Light Brown with Red Sandy Silt	Very Dense Light Grey Silty Sand
15	-	-	-	-	Hard Medium Brown Sandy Silt	Hard Light Brown Sandy Silt	Hard Light Brown Sandy Silt
16.5	-	-	-	-	-	Hard Medium Red Sandy Silt	Hard Medium Red Sandy Silt
18	-	-	-	-	-	Hard Medium Brown Sandy Silt	Hard Medium Brown Sandy Silt
19.5	-	-	-	-	-	-	Hard Medium Red Sandy Silt

From Figure 9, the trendline of SPT and SASW is almost similar though the difference may be considered large. The highest bearing capacity is recorded at 577.91 kN m^{-2} for SASW. However, the MP and SPT have a bearing capacity of approximately 213.98 kN m^{-2} up to 421 kN m^{-2}. Hence, the type of soil found in BH-2 is the type of silty sand and the soil becomes hard yellowish-grey silt from firm yellowish-brown sandy silt with depth.

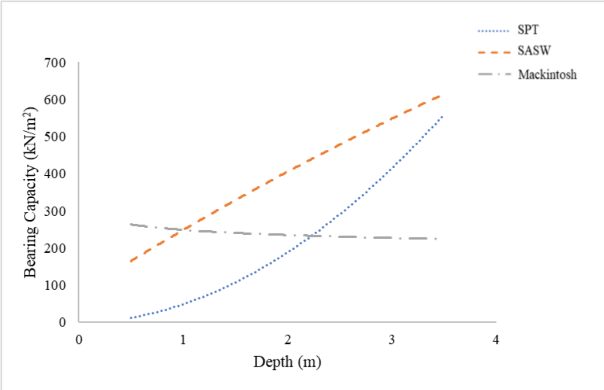

Figure 9. Bearing capacity obtained from SPT, MP, and SASW for BH-2

The value of MP test was consistent in BH-3 (see Figure 10). But the bearing capacity of SASW and SPT increased with depth and the trend is quite similar. By observing Table 1, the bearing capacity is supposed to increase as the soil type changes from loose brownish-grey sand to hard light-yellow sandy silt. MP test recorded the bearing capacity value with reading 426.8 kN m^{-2} while followed by SPT of 501.43 kN m^{-2} and finally SASW with 217.45 kN m^{-2} at 1.5 m. Moreover, the bearing capacity is 324 kN m^{-2}, 617.99 kN m^{-2} and 501.174 kN m^{-2} for MP, SPT and SASW respectively at 3 m and 256.24 kN m^{-2}, 546.51 kN m^{-2} and 499.52 kN m^{-2} at 4.5 m.

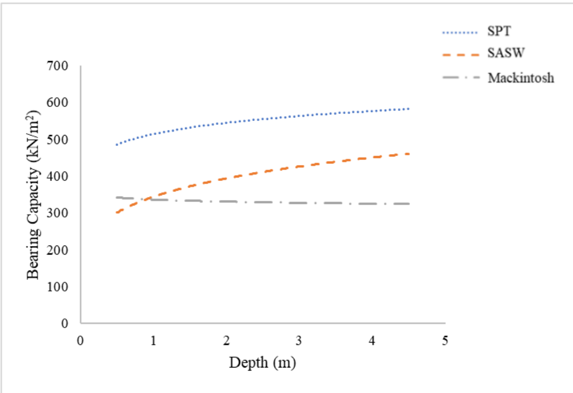

Figure 10. Bearing capacity obtained from SPT, MP, and SASW for BH-3

At the BH-5 location, the bearing capacity is higher in MP than SPT and SASW but SASW follows a similar trend as MP and SPT which is shown in Figure 11. The soil type found for this borehole was also sandy silt which also becomes harder with the depth.

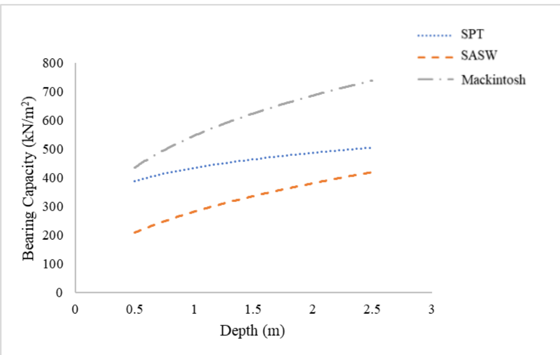

Figure 11. Bearing capacity obtained from SPT, MP, and SASW for BH-5

In BH-6, all the tests follow a similar pattern and the bearing capacity determined from SASW exactly matches with MP (see Figure 12). The soil type was found as brown sandy silt of this borehole. The soil type was firm up to 3 m, then it becomes stiff light grey sandy silt at 4.5 m, stiff medium at 6 m, very stiff at 7.5 m, very stiff medium sandy silt at 9 m, hard medium sandy silt at 12 m and continues up to 18 m. That means the bearing capacity increases gradually.

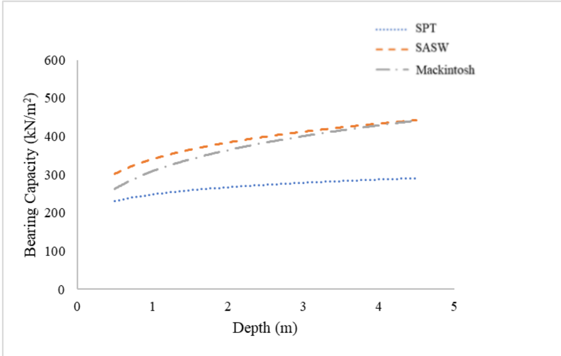

Figure 12. Bearing capacity obtained from SPT, MP, and SASW for BH-6

The bearing capacity from the MP exactly matches the SASW in this BH- 7 shown in figure 13.

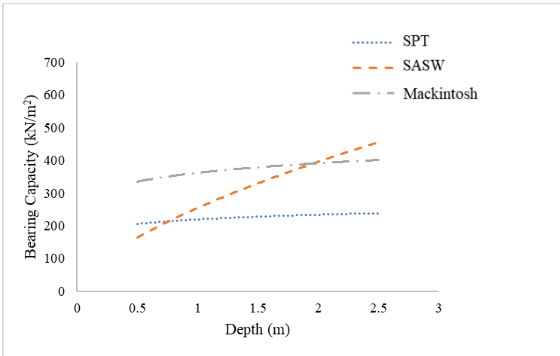

Figure 13. Bearing capacity obtained from SPT, MP, and SASW for BH-7

All of the tests show a similar pattern in this borehole. The soil type varies from firm medium brown sandy silt 1.5 m depth to hard medium red sandy silt at 19.5 m depth.

V. CONCLUSION

It is essential to evaluate the bearing capacity of soil with high precision for foundation design. This parameter of soil defines whether it can withstand the load of the structure without undergoing shear failure or excessive settlement or not. Although the shear wave velocity profile from the SASW method needs to be analyzed by skilled individuals, conventional testing such as SPT, MP are destructive, time-consuming, costly and laborious in terms of wide site area. This study reveals that the bearing capacity measured by SASW is comparable with the conventional SPT and MP tests. The coefficient of determination (R^2) between SPT and SASW is 0.95, 0.74, 0.81 and 0.91m for BH-2, BH-3, BH-5, and BH-6 respectively. And it is 0.43, 0.56, 0.58, 0.65 and 0.77 for BH- 3, BH-4, BH-5, BH-6 and BH-7 respectively for MP and SASW test. The overall R^2 found for SPT and SASW is 0.87 and 0.74 for mackintosh and SASW in all boreholes. Therefore, SASW has the potential to determine the ultimate bearing capacity as an alternative to SPT and MP tests.

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