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THE UTILIZATION OF DYNAMIC PROPERTIES IN DETERMINING PILE BEARING CAPACITY

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ABSTRACT

Recently, the techniques in geotechnical engineering design based on shear wave velocity measurement have had positive effects on the development of Spectral Analysis of Surface Wave (SASW) test. This SASW test has been shown to give reasonable results for in-situ measurements of shear wave velocity. In this study, the used of shear wave velocity and damping is being successfully applied to determine the ultimate pile bearing capacity. The method based on the viscoelasticity soil model proposed by (Abbiss, 1983) and the equation of the relationship between hyperbolic shear strain and shear stress suggested by (Hardin and Drnevich, 1972) has been used in this study. Further, the results from SASW and Instrumented Pile Load (IPLT) test that has been conducted at a site of residual soils located in Damansara, Selangor were compared. The results of the numerical calculation indicate that the percentage error in the ultimate pile bearing capacity is -1%, achieved the standard acceptance in the geotechnical engineering design.

Keywords: ultimate pile bearing capacity, shear wave velocity, dynamic strain, damping, SASW test.

INTRODUCTION

An evaluation of ultimate pile bearing capacity is very useful since it is important to know the factor of safety against the ultimate value. The ultimate pile bearing capacity can be evaluated by means of two approaches. Two approaches for obtaining ultimate capacity of the pile are field and theoretical approaches. Unfortunately, for field approach, its time consuming and high cost in conducting pile load tests. Meanwhile, for theoretical approach, obtaining a good sample for laboratory testing is difficult and generally some disturbance associated with the sampling and testing procedures.

Since the seismic method is a proven and the result obtained more stable and reliable when compared with those of the conventional method (Brown, 1998; Stokoe, Rix and Nazarian, 1989; Stokoe *et al*., 1994), SASW test has been conducted in this study to determine ultimate pile bearing capacity using shear waves velocity and damping based on stress-strain soil behavior.

FUNDAMENTAL OF SEISMIC THEORY

Shear wave velocity

It is a common practice to estimate the bearing capacity of a foundation based on the shear wave velocity and damping obtained from the SASW test carried out as part of the site investigation. The use of geophysical surface wave techniques has found an increasing application in geotechnical engineering practice. The shear wave velocity, V_s obtained from SASW test is a soil property used to determine the dynamic shear modulus, G0 of the soil. Similar to the overburden stress correction used for penetration resistance (Rix, Lai and Spang, 2000; Brown, Boore and Stokoe, 1999), the measured Vs should be normalized first denoted as normalized shear wave velocity, Vs1.

$$V_{s1} = V_s\left(P_a / \sigma'_v\right)^{0.25} \tag{1}$$

P_a	=	atmospheric pressure,
σ'_v	=	overburden pressure of the soil layers

Shear strain amplitude and damping in soil deposits

Initial shear modulus can be defined as shear modulus at infinitely small-strain amplitude. It is therefore necessary to obtain shear strain amplitude in soil deposits when the SASW test is to be conducted. The shear strain amplitude, γ is defined as the ratio of peak particle velocity, υ, to shear wave velocity, V_s:

$$\gamma = \left(\upsilon / V_s\right) \tag{2}$$

At small strains, particle motion resulting from propagation of shear waves is nondestructive. As γ increases, the G_0 will decrease from the maximum small-strain value, G_{max}. In-situ tests have commonly been assumed to be small-strain and the measurement of shear wave velocity will be directly related to the maximum shear modulus (Tezcan, Ozdemir and Keceli, 2006). The appropriate shear strain must be known, as well as the appropriate modulus reduction with increasing shear strain.

Material damping refers to the energy dissipation within a soil mass during dynamic loading (Whitman, 1970). For small value of material damping, the quality factor and damping ratio can be defined as the resonance frequency divided by the bandwidth (Abbiss, 1986; Rix, Lai and Foti, 2001). The half-power bandwidth method has originally been developed in the field of structural dynamics to determine the damping ratio of a structure from the width of the peaks in the structure's frequency response function. It is verified numerically that this method is also applicable to the wave number content of

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the soil's response, resulting in the attenuation coefficient of the surface waves (Foti, 2003; Rix, Lai and Spang, 2000). Through the relationship of damping and shear strain (Abbiss, 1983), the characteristic of normal or shear strain can be determined using following equation:

$$D = \left(D_{\max} / 1 + \ln\left(1 + (e-1)(\gamma_r / 2\gamma)\right)\right) \quad (3)$$

D_{max}	=	maximum damping, 33%,
D	=	damping at elastic strain,
γ	=	shear strain at damping measured

Relationship between shear modulus and shear strength of soil

In soil dynamics the behavior of soil under loading is normally assumed to have viscoelastic properties. The model assumes physically that the spring property can be measured by the shear wave velocity and damping parameter of the soil. This model has been successfully adopted (Abbiss, 1983) in the calculations of settlement and has been able to predict both the short and long term settlement behavior of sites in stiff clay, chalk, landfill and soft clay.

Soil dynamics tests under cyclic loading, both in normal triaxial or shear test have shown common hysteretic behavior. The skeleton or the backbone curve of the hysteresis is known to follow the form of curve (Hardin and Drnevich, 1972). This curve can be expressed in the form of hyperbolic stress-strain soil model which the shear stress, τ of soil can be defined using the following equation:

$$\tau = \left(G_0 \gamma / \left(1 + (\gamma / \gamma_r)\right)\right) \quad (4)$$

G_0	=	shear modulus at small-strain (less than about 10^{-4} %),
γ	=	shear strain,
γ_r	=	characteristics of shear strain

So, the shaft capacity, Q_s can be obtained by estimating the shear stress generated along the shaft and the area of the pile shaft that contact to soil layers can be calculated as:

$$Q_s = 2\pi r.h.\int_0^z \tau \ dz. \quad (5)$$

Under dynamic loading (Nayan *et al*., 2015), the stress strain loop of soil is similar to the loop of the cyclic shear loading and a similar relationship expressed the normal stress, σ by:

$$\sigma = \left(E_0 \varepsilon / \left(1 + (\varepsilon / \varepsilon_r)\right)\right). \quad (6)$$

E_0	=	elastic modulus at small-strain (less than about 10^{-4} %),
ε	=	normal strain,
ε_r	=	characteristics of normal strain

Then, the pile base capacity, Q_b can be calculated by the product of the normal stress, σ and area of pile base, A_b as following equation:

$$Q_b = A_b.\sigma \ . \quad (7)$$

METHODOLOGY

Field testing

The field measurements were conducted using a seismograph and two vertical geophones having a natural frequency of 1Hz and geophone calibration factor is 400V/m/s. The test site was a residual soil site of meta-sedimentary origin where a 27th stories commercial building is to be build located at Damansara, Selangor. The configuration of field measurements was set up using Common Array Profiling (CAP) as suggested by (Joh Sung-Ho *et al*., 2005).

Four different seismic impact sources were used to generate energy over a broad frequency range; geology, rubber, steel and steel sledge hammer. The Standard Penetration Test (SPT), Spectral Analysis and Surface Wave (SASW) and Instrumented Pile Load (IPLT) test performed at the location has shown in Figure-1.

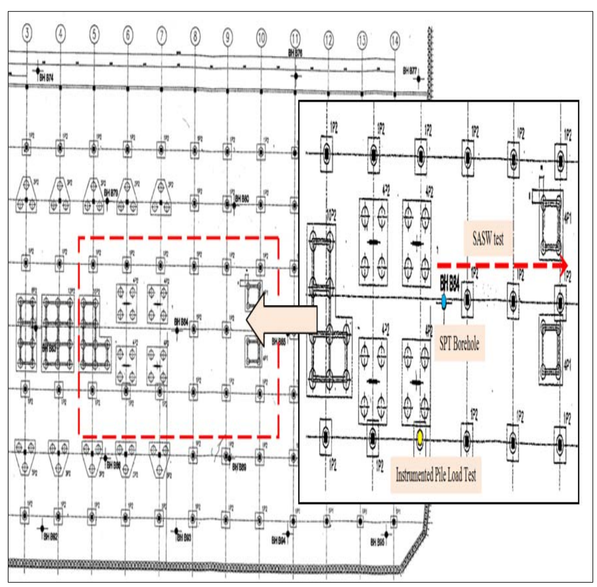

Figure-1. Site map with marked testing locations.

Site characterization

The SPT and SASW test results identifies numerous soil layers at the site indicate over 20.30 meters of medium dense silty sand, stiff sandy clay and silt which is a residual soil and has underlain by weathered rock deposit of granite as provided in Figure-2.

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The pile has a nominal diameter of 1200 mm and a penetration depth of 11.0 m from piling platform level. The pile was to be tested in the IPLT programmed to perfomed the strain of the pile and soil.

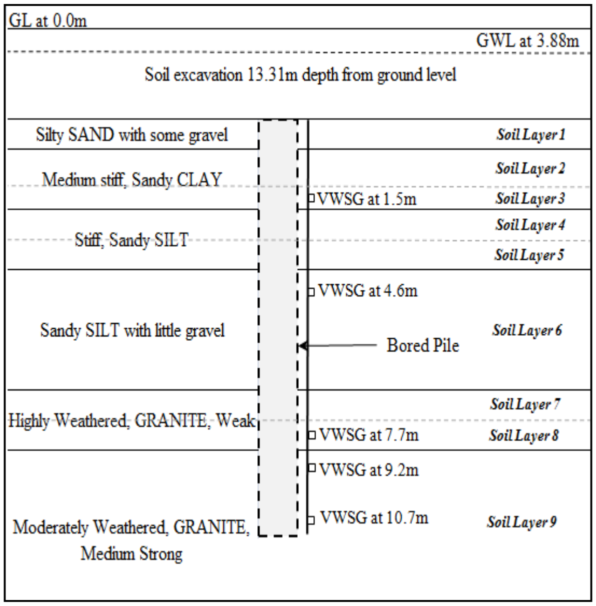

Figure-2. The soil profile of the test site.

RESEARCH FINDINGS

Shear wave velocity and normalized shear wave velocity from SASW test

The SASW data were carried out using the National Instrument USB6289 data acquisition system with the WinSASW 3.2.12 and analysis software. The direct comparison of the shear wave velocity, V_s and normalized shear wave velocity, V_{s1} profiles illustrated in Figure-3. The shear wave velocity, V_s structure is roughly divided into three sections, 0~6.45m, V_s is about 218m/s; 6.45~7.60m, V_s is about 257m/s; below 7.6m which encountored the rock formation, V_s is about 561m/s.

Illustration of the figure indicate that the V_{s1} profile significantly higher than V_s profile but when the profile entered to the rock formation, V_{s1} is smaller then V_s . As aforementioned in equation (1), the V_{s1} performed after consider the overburden pressure of the soil layer. Generally, the results of V_s and V_{s1} profiles reliable to the geological structure obtained from the SPT and IPLT test.

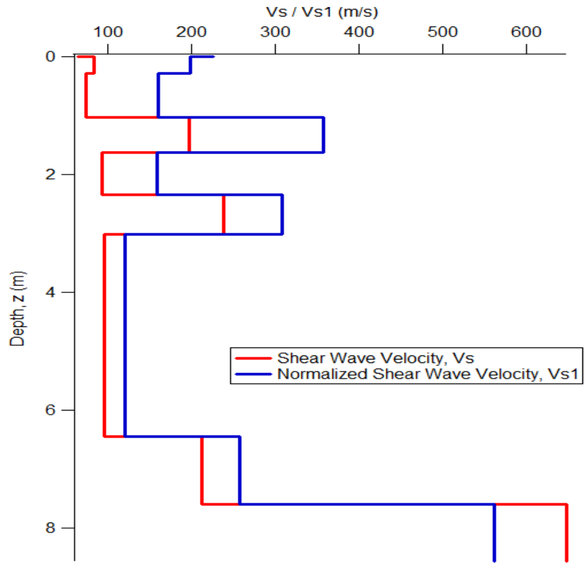

Figure-3. Profile of V_s and V_{s1} from SASW test at the site.

Shear strain amplitudes and damping ratio

During the SASW testing, the dynamic strain level caused by the shear waves can be estimated based on attenuation coefficient method. In this study, the time-trace curve obtained from Win SASW programmed has been selected to interpret the peak particle velocity generated by seismic source. Further, the shear strain amplitudes for all sources as presented in Figure-4 can be determined by using equation (2).

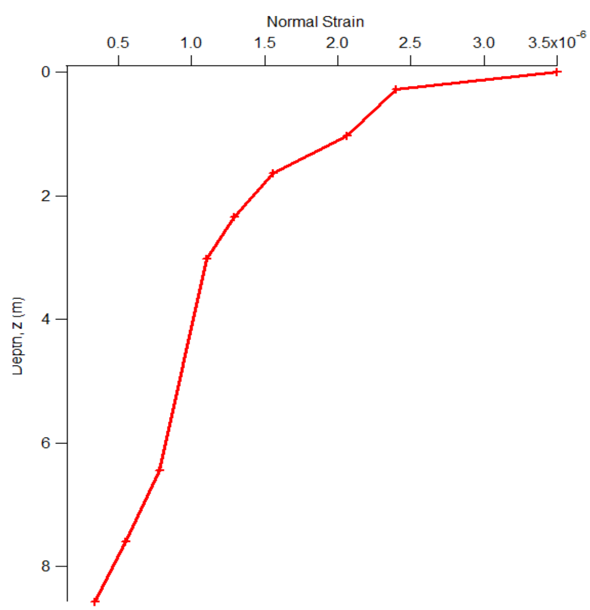

Figure-4. Profile of normal strain of soil deposits.

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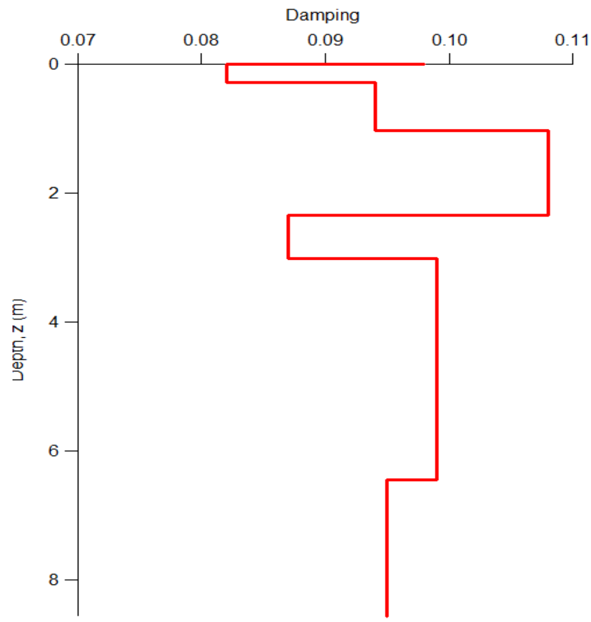

Figure-5. Profile of damping of soil deposits

Meanwhile, to measure the damping of soil from the signal spectrum recorded from SASW test, the half-power bandwidth method has been used for the interpretation of frequency-response curve using equation (3). The results of damping from the interpretation on frequency-response curve obtained from WinSASW programmed has shown in Figure-5.

Generally, SASW method predicted similar characteristics of normal strain and damping, which decreased with depth. Analysis of the performed SASW field data in this study shows that the strain amplitudes caused by several assorted hammer as seismic source are generally less than 10^{-6}%. From this finding, clearly shows that SASW method tends to have a more linear behavior of soil and dynamic properties at small strains (10^{-4}% or less), conditions.

Pile bearing capacity based on shear wave velocity and damping

For foundation design based on hyperbolic model, the two most important parameters are the modulus and strain. By applying equation (4) until (7) on the surface test, the results and direct comparisons between IPLT and SASW of pile bearing capacity as tabulated in Table-1. The comparison has shown a close agreement between both method.

The result of ultimate pile bearing capacity of SASW test has a lower than IPLT because SASW test can be measured the dynamic properties of soil (shear modulus and damping) at small strain (10^{-4}% or less) level. The performed test in this study gave ultimate pile bearing capacity of 18014kN for IPLT test and 17924kN for SASW test, at small strain levels of about 10^{-6} to 10^{-7} %.

Table-1. Bearing capacity of reference bored pile based on IPLT and SASW methods.

Methods	Bearing Capacity of Bored Pile (kN)		
	Shaft Friction, Q_s	End Bearing, Q_b	Ultimate Bearing, Q_{ult}
Instrumented Pile Load Test	14541	3473	18014
This Study (SASW Test)	17331	593	17924
Error (%)	16	-486	-1

CONCLUSIONS

In general, the performed SASW test has shown that shear wave velocity and damping are strongly related to evaluate the ultimate pile bearing capacity. This is substantiate in this study by the small error obtained between the ultimate pile bearing capacity for the test sites where the error was found to be -1% which is less than 5% of the standard acceptance in the design of conventional civil engineering structures.

Thus, it is proved that the characterization of the physical properties of residual soil in terms of shear wave velocity, the strain amplitudes and the damping can be satisfactory obtained using the SASW test. In addition, SASW test may well be a practically and economically a great tool for engineers in measuring shear modulus at very small strain conditions compared to IPLT. Implication of the results and future research directions are also presented.

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