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Full paper

Determination of Ultimate Pile Bearing Capacity from a Seismic Method of Shear Wave Velocity in Comparison with Conventional Methods

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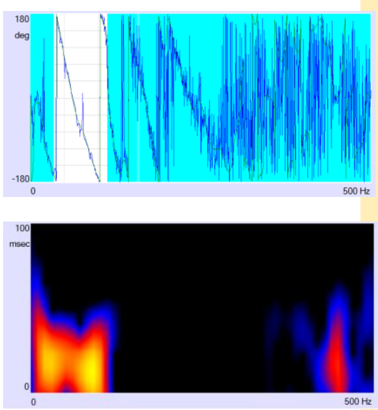
Graphical abstract



Abstract

The seismic method in the ultimate bearing capacity of piles based on shear wave velocity measurement is a new technique in geotechnical engineering design. In this study, the value of shear wave velocity, Vs is being successfully used to formulate a theory to determine the ultimate bearing capacity of piles. This theory is adapted from the ultimate bearing capacity of shallow foundation proposed by Keceli. Keceli's formula is adapted by equating the pile tip vertical resistance of the seismic formula to the end bearing capacity of the pile tip for each layer. The sum of half the vertical resistance of each layer is then equated to the total shaft resistance of the pile. The end tip is then added to the total shaft resistance to give the total ultimate pile bearing capacity of the pile. This study was conducted at three sites, two sites of residual soil located in Malaysia and one site of alluvial soil situated at Collierville, Tennessee, USA. The results of the adapted seismic formula were compared with the static pile bearing capacities calculated using conventional methods proposed by Meyerhof for the SPT-N values and the Schmertmann, Bustamante and Gianeslli method for the SCPTu values. The percentage error in the ultimate bearing capacity of the piles between the adapted seismic and the conventional methods for all the sites were found to be -4.77%, -3.01% and -0.93% at Hulu Langat, Mutiara Damansara and Collierville sites respectively.

Keywords: Pile bearing capacity; seismic methods; shear wave velocity

Abstrak

Kaedah seismos dalam menentukan keupayaan galas muktamad cerucuk berdasarkan pengukuran halaju gelombang ricih adalah satu teknik baru dalam rekabentuk kejuruteraan geoteknik. Dalam kajian ini, nilai halaju gelombang ricih, Vs telah berjaya diadaptasi dalam teori penentuan keupayaan galas muktamad cerucuk. Teori ini diubahsuai dari teori keupayaan galas muktamad asas cetek yang telah dibangunkan oleh Keceli. Formula Keceli disesuaikan dengan menyamakan rintangan menegak hujung cerucuk dari formula seismos dengan keupayaan galas hujung cerucuk bagi setiap lapisan. Jumlah bagi separuh rintangan menegak setiap lapisan ini disamakan dengan jumlah rintangan aci cerucuk. Rintangan akhir hujung cerucuk kemudiannya dicampur dengan jumlah rintangan aci untuk memberikan jumlah keupayaan galas muktamad cerucuk. Kajian ini telah dijalankan pada tiga lokasi tapak, dua tapak tanah baki terletak di Malaysia dan satu tapak tanah aluvium terletak di Collierville, Tennessee, USA. Keputusan adaptasi seismos ini telah dibandingkan dengan nilai keupayaan galas statik cerucuk menggunakan kaedah konvensional yang dicadangkan oleh Meyerhof bagi nilai SPT-N manakala kaedah Schmertmann, Bustamante dan Gianeslli digunakan bagi nilai SCPTu. Perbezaan peratusan pada keupayaan galas muktamad cerucuk seismos yang telah diadaptasi dengan kaedah konvensional bagi tiga tapak adalah -4.77%, -3.01% dan -0.93% bagi tapak Hulu Langat, Mutiara Damansara dan Collierville.

*Kata kunci:*Keupayaan galas cerucuk; kaedah seismos; halaju gelombang ricih

1.0 INTRODUCTION

There are various conventional methods in the calculation and evaluation of geotechnical bearing capacity of piles. Applications of conventional methods incorporate the use of basic soil parameters like friction angles and cohesion, vane shear, SPT-N, cone penetration and pressuremeter values. In order to determine the soil parameters, these methods may suffer problems related to disturbances that occurred during the sampling process, transportations and laboratory testing of samples. All these procedures are also time consuming. Furthermore, the final laboratory result may not be representative of the real condition of soil at the site.

In this paper, the seismic methods based on shear wave velocity (1981) and correspondingly the modification of Keceli's (2012) shallow bearing capacity formula is hereby proposed as an alternative to the conventional method in estimating the pile bearing capacity at three different sites. Accordingly, this seismic field method is simpler, faster, non-destructive, more environmental friendly and cost effective for the design of foundation.

Comparison of the pile bearing capacities from this seismic were then made with the normal empirical calculation using the SPT-N and SCPTu values.

■2.0 THEORY OF THE PROPOSED METHOD

Shear wave velocity is known to travel only in the matrix of soil particles and does not travel in its liquid part. This characteristic of shear wave velocity enables it to measure the effective soil strength in which it travels. The travelling shear wave causes minute strain and its measurement is known to be elastic and hence the dynamic soil properties were obtained.[1]

According to Keceli (2012), seismic impedance (Z) given as its density multiplied by its 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.[3] As such, the bearing capacity equation for shallow foundation based on the impedance value of soils irrespective of its depth is given by:

$$Z = \rho . V_s \quad (1)$$

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 1. The equivalent load or the overburden pressure at foundation level, q_f, is normally expressed as:

$$q_f = \gamma . d_f \quad (2)$$

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

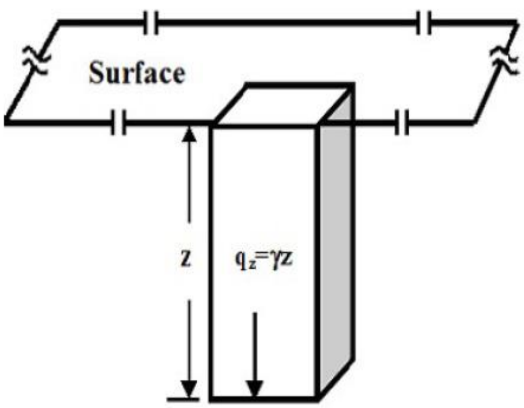


Figure 1 The soil column to cause bearing capacity failure[3]

If the overburden stress of soil of depth z as shown in Figure 1 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, pressure at the bottom of the soil column with the unit cross sectional area becomes:

$$q_z = q_u = \gamma_z = g.\gamma.z \quad (3)$$

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.

In order to evaluate ultimate bearing capacity, the value of z in Equation (4), is substituted with the product of V_S and T and the equation is then transform into:

$$q_u = g.\gamma.V_s\,.T \quad (4)$$

In terms of allowable bearing capacity:

$$q_a = q_u/1.5 \quad (5)$$

From standard values of the allowable bearing capacity of the most hard rock of V_S = 4000m/s, γ = 35kN/m^3 and q_a = 10Mpa, Equation (5) can be simplified to the following expression to obtain the ultimate bearing capacity of shallow foundation, given by:

$$q_u = 0.1\,.\gamma.V_s \quad (6)$$

From Equation (6), the unit weight of soil is obtained from its mass density using Keceli`s formula (Keceli, 2012)[3] as given in Equation (7). This equation is based on experimental shear wave values given by:

$$\rho = 0.44\, V_s^{\,0.25} \quad (7)$$

In pile foundation, the ultimate bearing capacity of Equation (6) is assumed to apply for the whole length of the pile. The total pile length is divided into segmental base of shallow foundation. Equivalent base bearing capacities for each segmental layers of the pile were based on their corresponding normalised shear wave velocities where the value of V_s in Equation (6), should be expressed as follow:

$$V_{s-n} = p_a/\sigma'_v \quad (8)$$

Where V_{s-n} is the normalized shear wave velocity, while $p_a$is the value of atmospheric pressure (101.325 kN/m^2) and σ'_v is effective overburden stress for each segment layers.

For each segment of the pile base, q_u is multiplied by the base area of the pile to obtain its ultimate resistance of each segment expressed as:

$$Q_{up} = q_u.A_{base} \quad (9)$$

The shear resistance in piles for each segmental layer of soil, $T_{us(n)}$ is hereby propose by the authors as in Equation (10) where the shear resistance is considered to be half of the ultimate tip resistance for the same segment.

$$T_{us(n)} = Q_{up(n)}/2 \quad (10)$$

The total shear resistance of the pile can then be equated to the summation of the skin resistance for every segmental depth given as:

$$Q_{us} = \sum_{n}^{1} \frac{Q_{up(n)}}{2} \qquad (11)$$

Where Q_{us} is known as total shaft resistance and $Q_{up(n)}$ is the pile tip resistance of each segment.

Finally the total ultimate pile bearing capacity can be given as :

$$Q_u = Q_{up} + Q_{us} \qquad (12)$$

The free-body diagram of these forces can be illustrated by Figure 2 shown below.

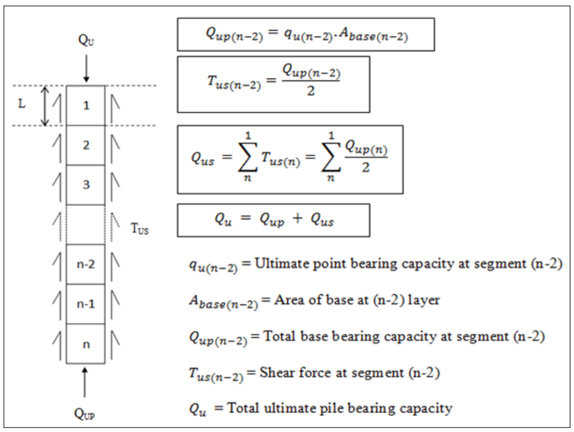


Figure 2 Adaptation of Keceli's formula to bearing capacity of pile

3.0 METHODOLOGY

The first site was a residual soil site of meta-sedimentary origin where a town hall is to be built at Hulu Langat, Selangor. The second site is a proposed commercial building and basement car park to be built at Nucleus Tower, Mutiara Damansara, Selangor and the third site is a sewage treatment plant at Collierville, Tennessee, USA.

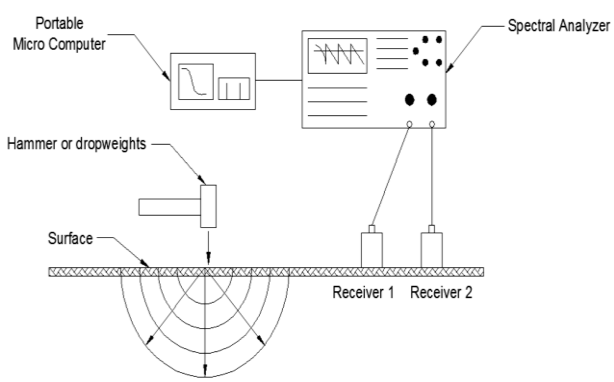


Figure 3 Configuration of the SASW test setup

The configuration of the SASW test has been set up as shown in Figure 3 using the Common Array Profiling (CAP) as suggested by Joh Sung-Ho *et al.* (2005) where the source to the first geophone spacing were set to 1D, 2D, 4D, 8D and 16D as shown in Figure 4, where D is the spacing between the two receivers.

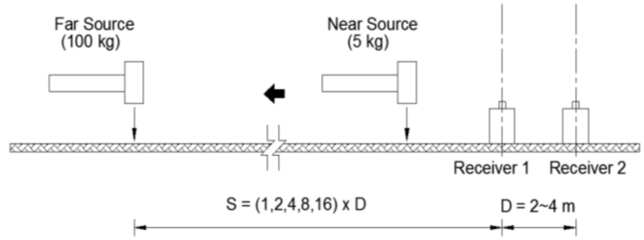


Figure 4 The layout of the CAP tests (after Joh). [6]

The SASW surveys of the two sites in Malaysia were carried out using the National Instrument USB6289 data acquisition system with the WinSASW 3.2.12 measurement and post-processing software developed by Joh (1996)[7]. The geophone sensors were of two 1-Hz geophone manufactured by Geostuff. Several assorted hammers starting with a small geological hammer to the sledge hammer of 8 kg in weight were employed. For the third site, data from the seismic piezocone (SCPTu) results at Collierville, Tennessee were obtained from the dissertation of Alexander Namie McGallivray (2007).[2]

All the shear wave velocity profiles for the three sites were then used in the Keceli's modified method as illustrated in Figure 2 to calculate the pile bearing capacity of several circular standard concrete piles as summerized in Table 1. Consequently piles of similar size were used to calculate their respective pile bearing capacities using conventional methods from SPT-N (Meyerhof, 1976)[8] field results. Meanwhile the conventional pile bearing capacity from the SCPTu results were then calculated using Schmertmann (1978)[5], Bustamante and Gianeslli(1982)[5] methods respectively. All the results were tabulated in Table 2 for comparison and evaluation.

4.0 RESULTS AND DISCUSSION

The soil profiles with their respective SPT-N values for the Hulu Langat Town Hall site and the commercial building and basement car park of Nucleus Tower site are given in Figure 5 and Figure 6 respectively. Correspondingly, Figure 7 shows the SCPTu values and Vs profiles at Collierville sewage treatment plant. The soil profiles are obtained by refering Soil Behaviour Type (SBT) chart by Robertson *et al.* (1986) based on CPT cone resistance,q_t on a log scale with friction ratio, R_f on a natural scale (Robertson, 2010).[9]

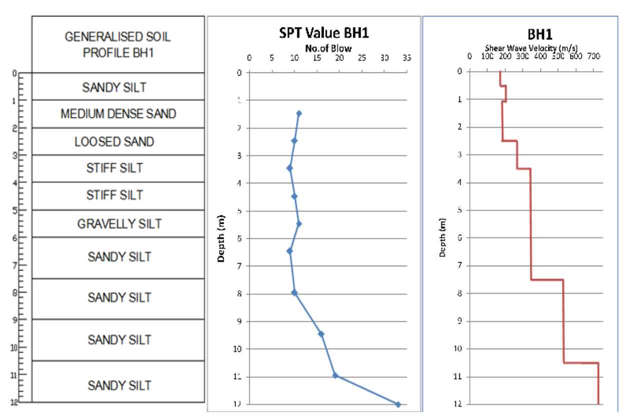


Figure 5 Soil profiles of SPT-N and SASW test at Hulu Langat, Selangor

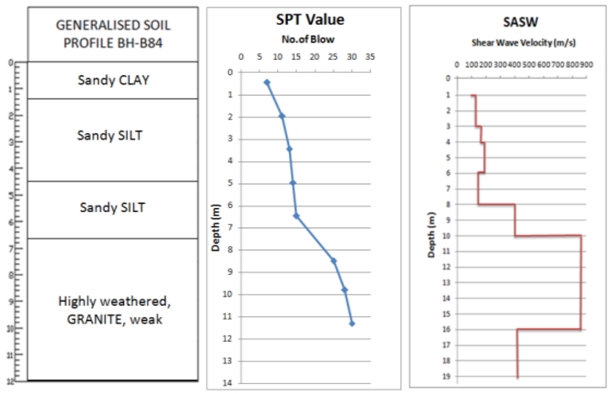


Figure 6 Soil profiles of SPT-N and SASW test at Mutiara Damansara, Selangor

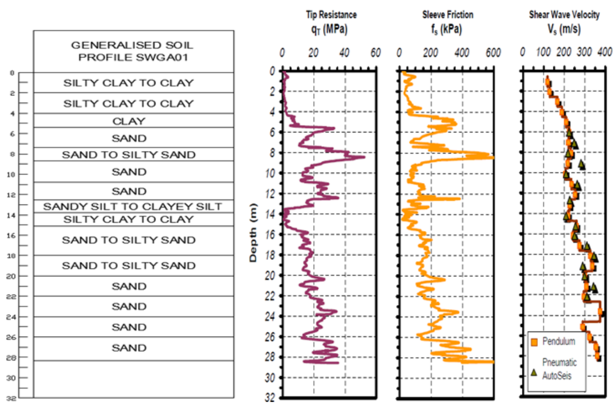


Figure 7 The SCPTu and SASW test at Collierville, Tennessee, USA[2,9]

Table 1 Conventional method applied for each site repectively

No	Site Location	Pile Length (m)	Pile Diameter (m)	Conventional Method
1	Hulu Langat, Selangor	11	1.2	Modified Meyerhof (1976)[10]
2	Mutiara Damansara, Selangor	11	1.2	Modified Meyerhof (1976)[10]
3	Collierville, Tennessee	11	1.2	Schmertmann (1978), Bustamante and Gianeslli(1982)[5]

Summary of results from the calculated pile bearing capacities using Equations (6)–(10) for these three sites were given in Table 2. The total percentage errors of the ultimate pile bearing capacities were found to be -4.77% and -3.01% for the corresponding residual site of Hulu Langat and Mutiara Damansara respectively. Correspondingly the percentage error of the ultimate pile bearing capacity for the alluvial soil at Collierville site was found to be -0.93%. The negative values of percentage errors in the ultimate bearing capacities that were obtained for all the sites indicates that the values from the seismic method are all lower than the conventional methods. This study has shown that the seismic methods are slightly more conservatives as compared to the conventional methods. The phenomena maybe attributed to the difference in the coverage offered by seismic methods and the conventional methods where the former is three dimensional and the later is one dimensional in terms terms of the tets coverage of the site.

Table 2 Comparison between conventional and seismic method of ultimate pile bearing capacity

No	Site Location	Ultimate Bearing Capacity, Qult		Error
		Conventional (kN)	**Seismic (kN)**	**(%)**
1	Hulu Langat	11605.20	11051.30	-4.77
2	Mutiara Damansara	12729.83	12346.74	-3.01
3	Collierville	2426.75	2404.23	-0.93
			Average Error	-2.90

5.0 CONCLUSION

The performed seismic tests have shown that the shear wave velocity profiles are strongly related to the ultimate pile bearing capacities. This is substantiate in this study by the small differences obtained between the ultimate pile bearing capacities for the three sites where the average error was found to be 2.90% which is less than 5% of the standard acceptance in the design of conventional civil engineering structures. Further improvement could be attained with further studies to be carried out in order to explore the potential of the propose seismic method mentioned herein in this paper.

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