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ARTICLE

INVESTIGATION OF THE SHEAR WAVE VELOCITY AND DAMPING MEASUREMENTS, TO BE CONDUCTED (*IN SITU*) ON SOFT CLAY, TO TEST ITS SHEAR STRENGTH

Bukhari R[1*], Khairul Anuar M. N[2], Anuar K[3], Roszilah H[4], Kowstuba R[5], Colin Peter A[6], Mohamad Noh O[7]

[1, 2,3,4,5] *Civil and Structural Engineering Department, Universiti Kebangsaan Malaysia, Bangi, MALAYSIA*
[6] *Former Senior Research Officer, Building Research Establishment, Watford, UNITED KINGDOM*
[7] *Director, Road Engineering & Geotechnical Works Division, Public Works Department, MALAYSIA*

ABSTRACT

This is an efficient conventional Engineering seismic test that is carried out on soft soil samples. It is widely preferred due to reduction in disturbances on samples; non-destructive method, physical mitigation of the problem of stress relief, accurate- inherent errors are minimal, compared to results from other tests. The known values to the equation are the shear wave velocity and the strain. These values are calculated after conducting the Plate Load Test; damping is done at a strain level which is determined during the test. The proposed equation will produce a stress-strain (shear) relationship which will enable the plotting to failure point; the failure strain level of 4% indicating the maximum possible shear strength. The Plate Load Test strain data is the basis for the equation. This equation over-estimates the shear strength values, by a margin of about 32 and 1.3 % at depths of 2.0 and 5.0 m respectively. However, its results are more accurate than those of the Geonor Vane test; measurements of un-drained shear strength and sensitivity of soft clays, *in situ*.

INTRODUCTION

KEY WORDS
Shear strength, shear velocity,, Plate Load Test, Damping

Shear strength of clay can be scientifically defined as the maximum resistance of a soil, just near shear failure- due to structural loads subjected to the soil [1]. Clays can be subjected to either field, *in situ,* tests or laboratory tests [2]. Common laboratory tests are:

The Unconsolidated Undrained Triaxial Test (UU Triaxial Test),

- The Isotropically-Consolidated Undrained Triaxial Test (CIU Triaxial Test),
- The Unconfined Compression Test (UCS Test),
- The Shear Box Test.

Common *In situ* tests include:

- Vane Shear Test,
- Piezometer Cone Penetration Test (CPTU),
- Geonor Vane Test,
- Acker Vane Test.

All these methods have their limitations.

In the research, the UU Triaxial Test, CIU Triaxial Test, Piezometer Cone Penetration Test, Geonor Vane Test and Acker Vane Test were considered.

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The **Unconsolidated Undrained Triaxial Test (UU Triaxial Test)** measures the shear strength of a soil by not consolidating the specimen [3], thus drainage is not permitted either during application of cell pressure or at the point of shearing [4].

The **Isotropically-Consolidated Undrained Triaxial Test (CIU Triaxial Test)** involves three stages [5]. These are:

- saturation stage- application of a back-pressure (undrained condition),
- consolidation stage- the specimen is brought to the state of effective stress (isotropic),
- Shearing stage- during compression/consolidation, the cell pressure is kept at a constant as the soil sample is sheared at a constant rate of strain.

The **Piezometer Cone Penetration Test (CPTU)** involves the direct penetration of a 60 degrees cone of about 35.8 mm diameter. The equipment is pushed by a hydraulic force. The resistance and pore pressure of a soil are measured [6]. According to Huang [7], advantages of this test are that:

- the soil is displaced without creating any soil cuttings,
- the tools are small, thus minimal intrusion,

***Corresponding Author**
Email:
bramli99soa@gmail.com
Tel.: + 60-1123118199
Fax: + 60 389118344

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- no fluids are required for penetration,
- the equipment measures the equilibrium pore pressure at full PPD,
- The test allows for empirical and theoretical correlation of piezocone measurements to some soil parameters.

The Geonor Vane Test is the most widely used method for measuring the shearing resistance and sensitivity of soft to medium stiff clays in the field. It is conducted at undrained conditions. The test employs the use of various vane sizes. The Geonor H-70 can bore to a depth of 10 metres by hammering, pressing or drilling.

The Acker Vane Test is performed on undisturbed soft soils; thus, no much resistance is required [8]. The vane equipment is usually designed for hand operations. The whole assembly consists of samplers, tubes and earth augers. Fast and accurate readings can be obtained for depths of up to 30.5 metres.

An alternative method was considered in this research; shear wave velocity and damping measurements. The experiment involved comparison of results with the laboratory methods conducted on a soft clay- origin: Klang, Malaysia.

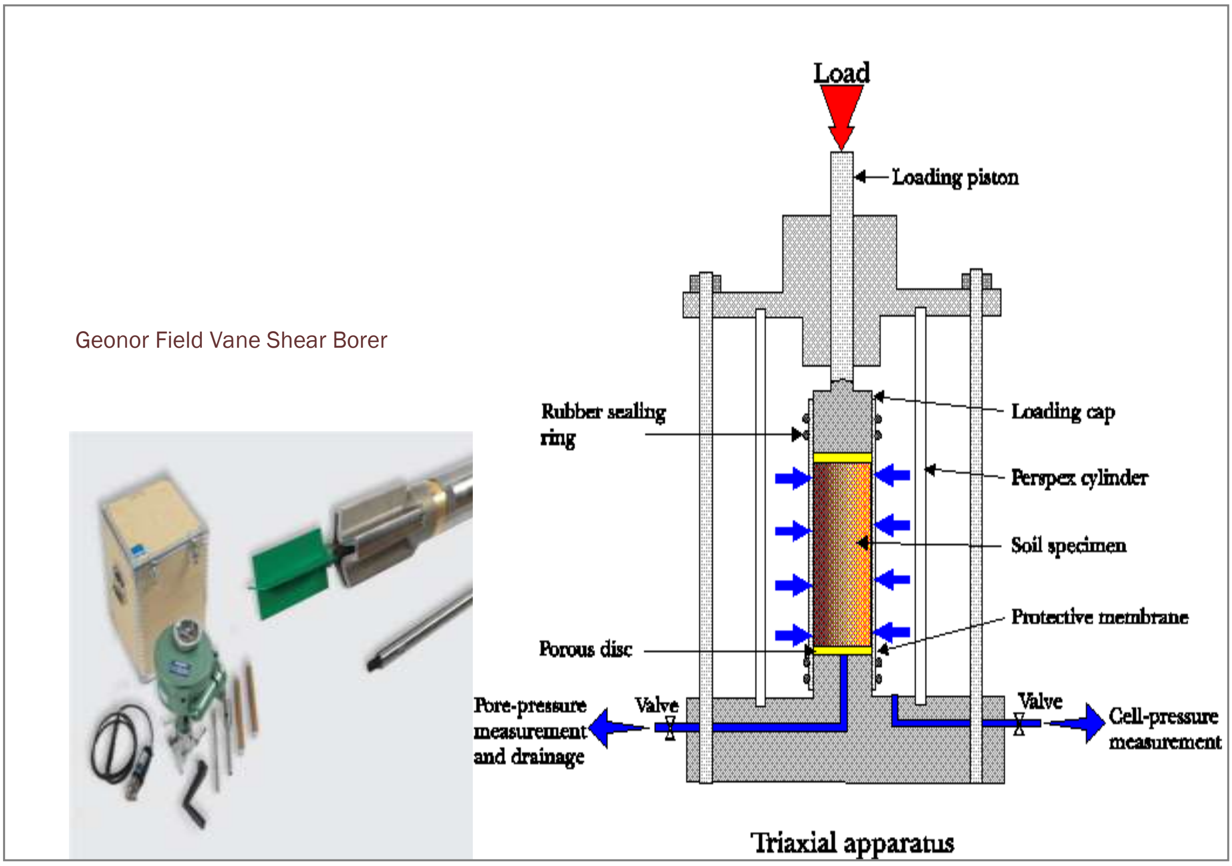

Fig. 1: Geonor Vane Test and Triaxial Tests Apparatus (Courtesy: Google)

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Symbols

D	Damping
Dmax	Maximum damping, whose value is 33%
Go	Shear modulus
E	Energy
Δ	Change in
E	Euler constant
γ	Shear strain
τ	Shear stress
$\Delta\sigma_v$	Deviator stress
γ_r	Characteristic shear strain

ε Strain

τ_f Shear strength

υ Poisson's ratio

1. The viscoelastic soil model

In this study, the property of viscoelasticity is considered. This is the property of a material exhibiting both elastic and viscous characteristics, during deformation- e.g. at settlement. Viscoelasticity calculations greatly depend on the following variables:

- viscosity/fluidity,
- Temperature.

The value of viscosity or fluidity is a function of the temperature or as a certain value- dashpot [9].

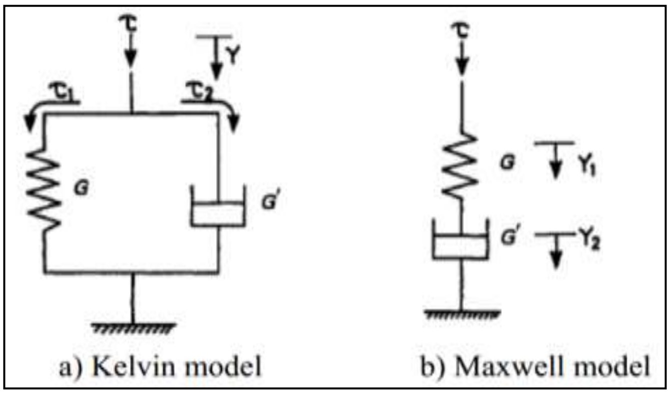

Fig. 1: A typical viscoelastic soil model [9].

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Soils exhibit nonlinear stress-strain behavior; which can be represented by models which obey the real stress-strain path during cyclic loading. The shear strength of a soil sample can be accurately represented, and with a pore pressure model, changes in stress (effective) during cyclic loading for un-drained conditions [10]. The following hyperbolic backbone function, Eq. (1), illustrates the performance of nonlinear cyclic models. Three functions are of great importance:

- shear modulus,
- characteristic shear strain,
- Shear stress.
- $$\tau = G_0\gamma / [1+(\gamma/\gamma_r)] \quad (1)$$

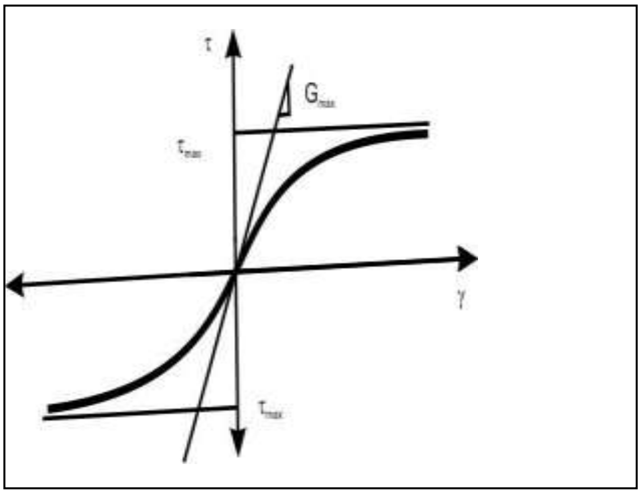

Fig. 2: The hyperbolic backbone curve [5].

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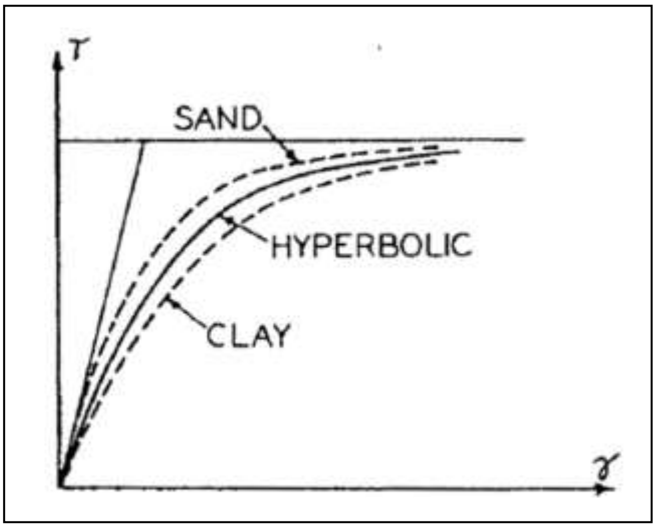

Fig. 3: Hyperbolic stress-strain relation [11].

At maximum shear strain,

$$\tau_{\max} = G_0 \gamma_r \qquad (2)$$

A plot of shear stress (τ) versus shear strain (γ), can be used to determine the unknown parameter (γ_r) from the relationship of damping and strain [12],

$$D = D_{\max} / (1 + \ln[1 + (e - 1)(\gamma_{r/} 2\gamma)] \qquad (3)$$

The equivalent shear strain is found from the axial strain. This is represented in the elastic relationship below.

$$\gamma = \varepsilon(1 + \upsilon) \qquad (4)$$

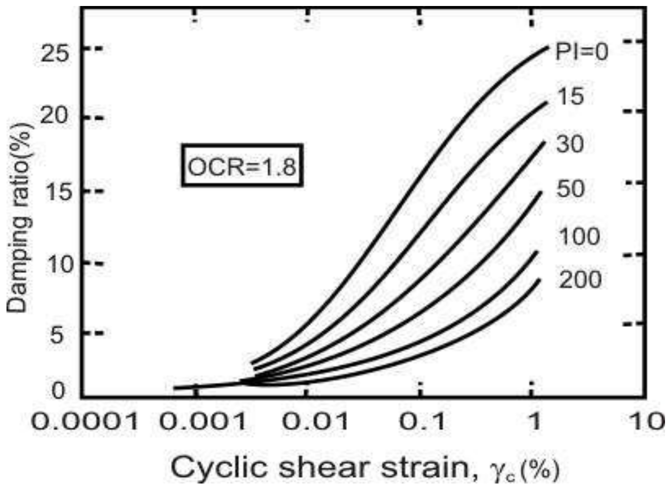

Fig. 4: Variation of damping ratio with cyclic shear strain, for clays [13].

Damping ratios of very soft clays are lower than those of coarse-grained soils, at the same cyclic strain amplitude [14]. Hysteresis loops, in physics, involves energy dissipation, hence vibration damping [15]. The more the hysteresis in the stress-strain curve, the greater the loss of energy, hence the higher the damping ability [16].

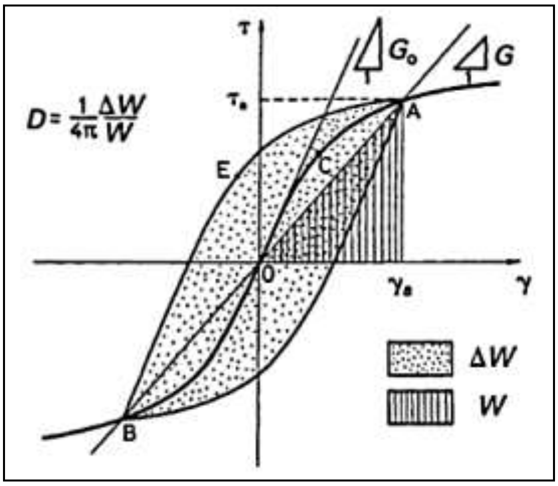

Fig. 5: Damping- hysteresis loop, as a stress-strain curve [16].

Using the hysteresis loops, damping *D* is calculated from the energy loss.

$$D = \Delta E \, / \, 4\pi E \tag{5}$$

Experimental evidence shows that some energy is lost at low strain levels [17]. Therefore, there is always a value of more than 1, of the damping ratio. The width of the loop exhibited by a soil under cyclic loading conditions increases with increasing amplitude of the cyclic strain [18].

The Isotropically-Consolidated Undrained Triaxial Test can be used to find values of shear stress and shear strain and a plot of these achieved [19]. [20 proposed the reference shear strain γ_r which has been illustrated below.

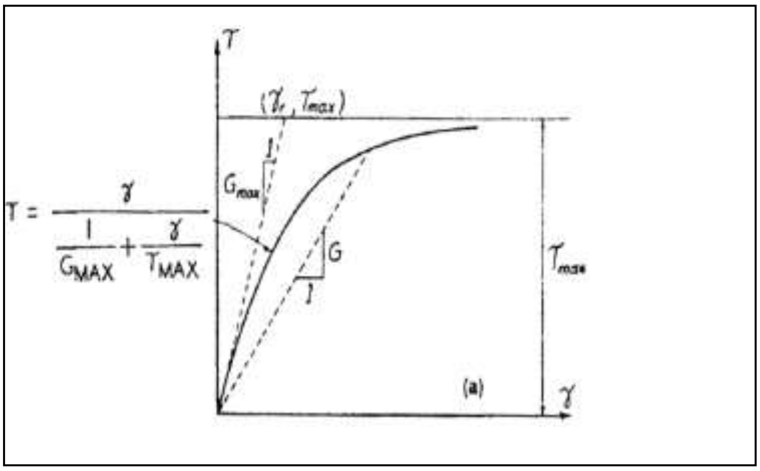

Fig. 6: The Plate Load Test reference strain curve.

RESULTS

A layout of the geotechnical site investigation tests is presented as shown below, showing the Spectral-Analysis-of-Surface Waves (SASW) and the rest of the test.

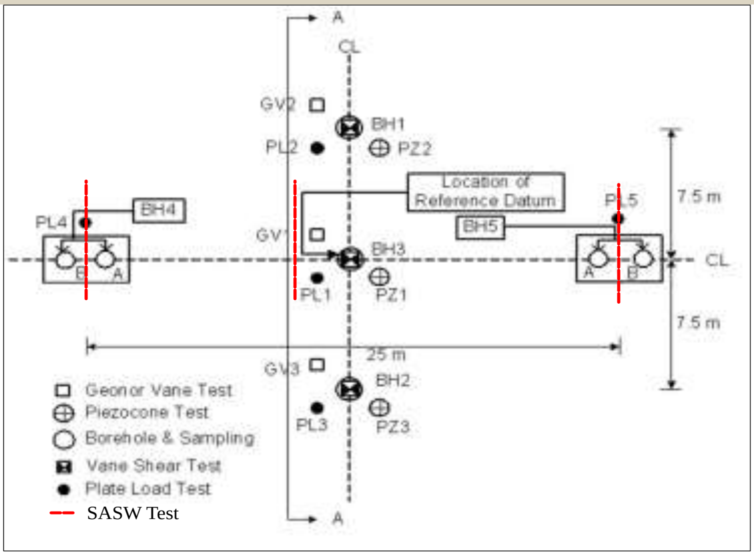

Fig. 7: Layout of the geotechnical site investigation tests.

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The SASW test is a seismic technique for obtaining the shear wave velocity profile of soil samples. Advantages of this test are that:

- It is a non-invasive *in situ* technique [21],
- it is faster than other similar methods [8],
- it incur low cost [8],
- it can be used where site subsurface conditions may hinder the use of probes and boreholes [22],
- it can be used to estimate the damping ratio profile of a soil sample [22].

The site's geology has been identified as that of quaternary alluvium, derived from soft marine clay, with some organic materials. Marine clay is usually found in coastal regions [23]. A loose, open structure of clay particles is formed in the process [24]. It is prone to swelling [25] and has the potential to destroy building foundations [26]. The soil profile and its properties are shown in the figure below.

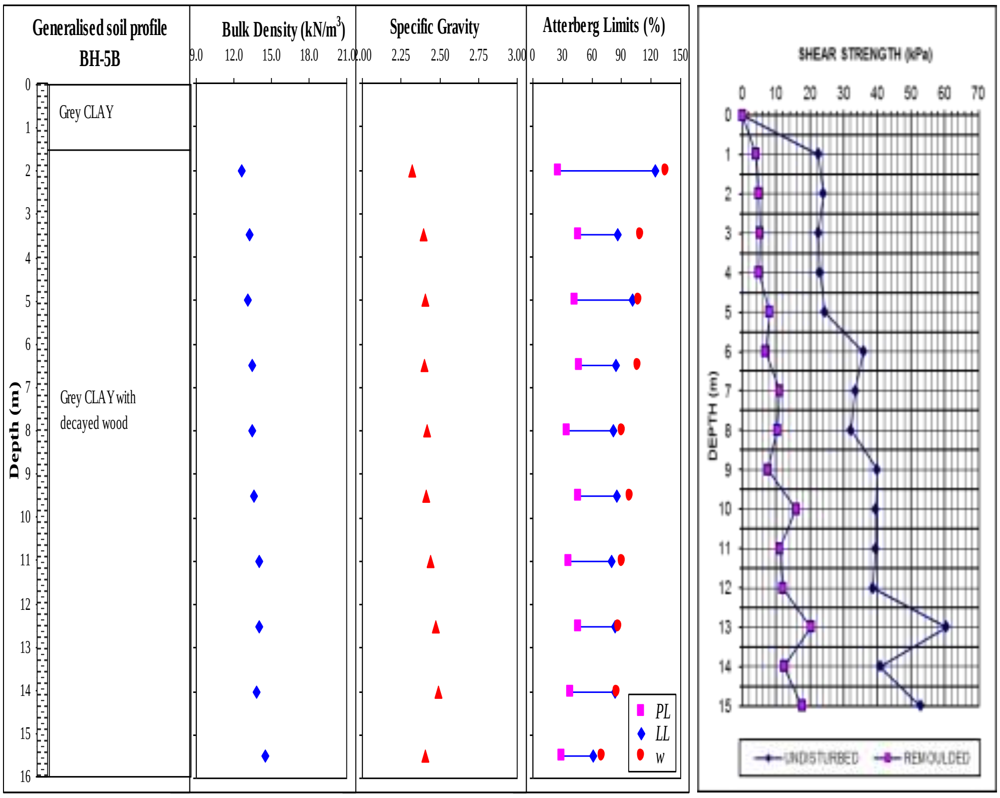

Fig. 8: Profile, basic properties and shear strength of the existing soil, at site.

Eq. (1) was used to find the values of shear stress and shear strain, and show their relationship. This has been illustrated below.

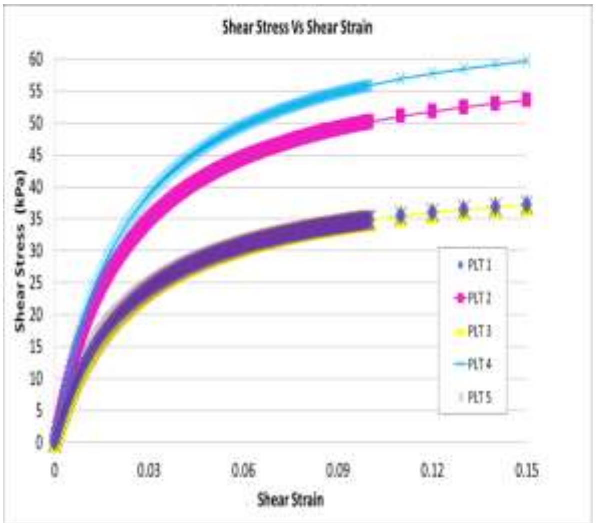

Fig. 9: Shear stress and shear strain relationship. A typical diagram is represented by [27].

Various field and laboratory tests were conducted and their shear strength values compared to the proposed equation at 4% strain, using the Plate Load Test reference strain data.

Table 1: The shear strength of soil samples, evaluated from all conventional methods at a depth of 2.0 m.

				Shear strength (KN/m^2)		Average (KN/m^2)	Difference compared with the Geonor Vane Test (%)
Test location	1	2	3	4	5		
Proposed equation at 4% strain, using the PLT reference strain data	27.1	39.0	27.1	43.5	27.1	31.0	32.0
Total Stress (UU Triaxial Test)	-	-	-	-	12.4	12.4	-47.2
Effective stress (CIU Triaxial Test)	-	-	-	-	4.6	4.6	-80.4
The Piezometer Cone Penetration Test (CPTU)	8.3	7.4	8.8	-	-	8.2	-59.8
The Geonor Vane Test	26.0	20.6	24.0	-	-	23.5	-
The Acker Vane Test	-	-	15.2	-	-	-	-35.3

Table 2: The shear strength of soil samples, evaluated from all conventional methods at a depth of 5.0 m.

				Shear strength ($KN/m2$)		Average ($KN/m2$)	Difference compared with the Geonor Vane Test (%)
Test location	1	2	3	4	5		
Proposed equation at	27.1	37.0	27.1	43.5	27.1	32.4	1.3

4% strain, using the PLT reference strain data							
Total Stress (UU Triaxial Test)	-	-	-	-	29.5	29.5	-2.5
Effective stress (CIU Triaxial Test)	-	-	-	-	11.1	11.1	-65.3
The Piezometer Cone Penetration Test (CPTU)	14.1	19.1	20.2	-	-	17.8	-44.4
The Geonor Vane Test	29.0	37.0	30.0	-	-	32.0	-
The Acker Vane Test	-	-	21.0	-	-	-	-34.3

DISCUSSION

The maximum shear strength corresponds to the estimated value of the maximum shear strain, at the point of failure [28],[29]. The maximum strain is found from the level of strain of the Isotropically-Consolidated Undrained Triaxial Test (CIU Test) of the laboratory samples; the initial strain of the soil samples up to failure being about 4.2%.

Three Geonor Vane tests and Peizocone tests were evaluated. It was observed that all the test values for the other conventional methods were lower than the individual values of the proposed equation. Though there was consistency of obtained values, there are some errors in the experiment. This may include:

- Insufficiency of samples used, thus the average value of the shear strength is not very reliable or accurate. About 25 Cone Penetration Tests (CPTU) need to have been conducted [30],
- the penetration pause effect- on cone tip resistance [30],
- equipment and calibration errors [31],
- human errors such as wrong counting and non-consistent drop height [31],
- computation-spring factor [32],
- clay with organics [32].

In the comparison, the Geonor Vane Test was chosen as the standard test since it was reported as the best method for estimation of the shear strength of soft clay [33]. According [34] the Geonor Field Vane Shear Borer is considered efficient because:

- it is fully protected and pressure push-in,
- there is no friction between the rod and the soil due to its tube protected rods,
- The protection shoe protects the vane and cleans it automatically before each measurement. The shoe is very useful for testing in sites with stratified, sandy, gravelly and marine sediment clays.

Negative values of the percentages indicate an underestimation of the shear strength while positive values of the percentages indicate an overestimation of the shear strength.

At 2.0 m depth, the UU Triaxial Test, CIU Triaxial Test and Acker Vane Test underestimated the shear strength by 47.2 percent, 80.4 percent and 35.3 percent respectively. Shear strength calculated using the equation, at 4.0% strain, and for PLT reference strain data overestimated it by 32 percent. A similar pattern is obtained at the 5.0 m depth and at other subsequent depths. At the 5.0 m depth, the UU Triaxial Test, CIU Triaxial Test and Acker Vane Test underestimated the shear strength by 2.5 percent, 65.3 percent and 34.3 percent respectively. Shear strength calculated using the equation, at 4.0% strain, and for PLT reference strain data overestimated it by 1.3 percent.

Major reasons for underestimation include:

- stress relief,
- Sample disturbances- inevitable damage is caused to the granular microstructure of the ‘nominally undisturbed’ samples.

The following experiment was subject to differences (overestimation and underestimation) in estimated values due to the nature of both methods. Differences in these methods, according to Powrie [35] are stated below:

- The proposed method applies a seismic method; waves are propagated into the soil (in a cylindrical form); this form is in all the three dimensions. In contrast, the conventional method is conducted in two dimensions,

- Only a test area within a diameter of 50mm or 100mm of the specimen can be represented, using the conventional methods. On the other hand, the seismic method covers a very large area of the site.

CONCLUSION

In comparison with the Geonor Vane Test, it was found that the proposed equation overestimated the shear strength while the conventional methods underestimated the shear strength, of the specimen. This situation is quite acceptable and reasonable since the seismic method (basis of the proposed equation) is non-destructive while the conventional methods are destructive [36].

RECOMMONDATION

It is extremely difficult to accurately correlate the two methods due to their inherent nature. Sufficient representative data of the conventional method is thus required, so as to cover an equivalent area of the seismic tests. However, this is considered uneconomical and impractical.

CONFLICT OF INTEREST

All the authors declare no conflict of interest with in this research.

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