

Determining Strength of Calcareous Sediments in a Geotechnical Centrifuge

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Summary This paper presents results obtained from centrifuge testing of calcareous sediments in order to determine their monotonic and cyclic strength properties. The focus of the paper is on the description of a new testing device for use in the centrifuge facility at The University of Western Australia. Capable of applying torsional loads to various probes, at speeds ranging from 0.2 to 340 deg/s, the equipment has been used to examine the monotonic strength of calcareous sediments through vane shear testing. The results of such tests are compared to those obtained from alternative strength characterisation methods. In addition, a new testing device called the Torsional Plate Load Test is introduced as a means of investigating the monotonic and cyclic properties of the soil.

1 INTRODUCTION

In the design of foundations for offshore structures, one of the primary areas is the determination of *insitu* soil properties. Such soil properties include those used to characterise the type of material, as well as monotonic and cyclic strength parameters, and consolidation coefficients. Typically, an *insitu* site investigation is conducted at the proposed location, and coupled with a detailed laboratory test program to determine the desired parameters. At present, field site investigation techniques include core sampling to determine material types and to obtain undisturbed samples for laboratory testing, and cone penetrometer (CPT) and vane testing to determine *insitu* soil strength.

The discovery of extensive oil and gas reserves in the extremely soft calcareous sediments characteristic of the North-West Shelf of Western Australia, where undrained shear strength profiles may be as low as 0.5 - 1 kPa/m, has led to engineers challenging the traditional testing techniques.

This paper details aspects of a centrifuge test program initiated at The University of Western Australia (UWA) to examine alternate types of *insitu* soil testing apparatus. Firstly, the T-bar and ball penetrometer are discussed and compared to results from traditional CPT testing in calcareous clay in the centrifuge. Discussion will then focus on the description of a new testing apparatus developed for the centrifuge able to conduct in flight rotation tests, with vane test results presented. Finally, a new rotation device is introduced and discussed as a possible device to examine both the monotonic and cyclic *insitu* strength properties.

2 EXISTING METHODS

As mentioned previously, existing *insitu* testing devices for offshore soil strength determination are the vane test and

CPT. However, limitations of both apparatus has led to alternative testing devices being examined. Before discussing the proposed alternative testing devices, a brief mention is made of the vane shear test and CPT.

2.1 Vane Tests

With respect to the vane test, the apparatus is only used in soft to medium strength soils due to the sensitivity of the equipment. This becomes a problem when testing in calcareous sediments, where soft soil layers are often separated by thin crusts of cemented material of variable strength.

To deduce undrained shear strength (s_u) from vane tests, the torque (T) required to rotate a cylinder of soil sheared by the vane probe is measured, and can be directly correlated to s_u using

$$s_u = \frac{T}{\pi d^2 (h/2 + d/6)} \quad (1)$$

where h represents the height of the cylinder (equal to the height of the vane probe) and d represents the diameter of the cylinder (equal to the diameter of the vane probe). A full discussion is provided in Scott (1). The geometry of the centrifuge vane used in the research program is further discussed in Section 4.2.

2.2 Cone Penetrometer

Unlike the vane test, the cone penetrometer is not subjected to limitations due to material layering. However, the use of CPT testing becomes questionable in extremely soft sediments. This can be explained by examining the corrections required in the analysis of CPT data.

Firstly, a correction must be made for the pore pressure at the shoulder of the cone (defined as the pore pressure area correction), and an estimate of the excess pore pressure generated during penetration of the cone is required. In the water depths typical of the new oil and gas fields (often > 300 m) this correction can be significant, and errors in estimating the excess pore pressure can lead to errors in interpreting the CPT results.

Secondly, to deduce net bearing pressure (q_{net}) the measured CPT results (q_m) must be corrected for the overburden stress (σ_v) due to the weight of the soil. In many cases the net bearing pressure may be roughly equivalent to the overburden pressure, which implies that small errors in deducing overburden pressure can result in significant errors in the deduced q_{net} .

In its simplest form, the relationship between measured cone resistance, net bearing pressure and overburden pressure can be expressed as (after Robertson and Campanella (2))

$$q_{net} = q_m - \sigma_v \quad (2)$$

Including the effect of area correction, where α is the area correction factor defined by Almeida and Parry (3), equation (2) becomes

$$q_{net} = q_m - \sigma_v + \alpha(u_0 + \Delta u) \quad (3)$$

where u_0 is the hydrostatic pore pressure and Δu represents the excess pore pressure generated during penetration of the cone penetrometer.

Further, excess pore pressure can be determined using

$$\Delta u = \beta q_{net} \quad (4)$$

where β represents the ratio of excess pore pressure to net bearing capacity. Combining equations (3) and (4), and acknowledging that $\sigma_v = \sigma'_v + u_0$, a general equation of the form

$$q_{net} = \frac{q_m - [\sigma'_v + u_0(1 - \alpha)]}{1 - \alpha\beta} \quad (5)$$

can be derived to deduce q_{net} from q_m .

Having determined q_{net} from equation (5), the undrained shear strength (s_u) is then calculated using (after Davies et al, (4))

$$q_{net} = N_{CPT} s_u \quad (6)$$

where N_{CPT} is a cone factor deduced from a combination of numerical and experimental testing. For this research program, N_{CPT} is approximately 10-12 which agrees well with other researchers. Field values of N_{CPT} are somewhat arbitrary, with reported values ranging from between 9 and 15 depending on over-consolidation ratio, soil structure and sensitivity, and cone design.

Given uncertainties in the various factors used to derive s_u , Randolph (5) demonstrated how even moderate errors in q_m ,

α , β , σ'_v and N_{CPT} can lead to errors in predicting s_u between +35 % and -25 %. This fact has been the driving force behind the design of alternative testing devices for offshore soils.

3 NEW PROBES

To overcome the shortcomings of the CPT in soft soils (such as the calcareous sediments typical on the North-West Shelf) two alternative probes have been examined as part of the centrifuge research program at UWA. These are the T-bar and ball penetrometer. Both penetrometers consist of a probe located at the end of thin shaft. The probe is penetrated into the soil stratum, and a load - displacement response generated. The two new probes are illustrated in Figure 1, which also shows the CPT and approximate soil mechanisms of the three devices during penetration. For this research project, the T-bar probe consists of a 5 mm diameter bar 20 mm in length penetrated into the soil in a direction perpendicular to the length of the bar. In the case of the ball penetrometer, the probe is simply a 12 mm ball located at the end of the shaft. In both cases the probe is sandblasted to generate a surface roughness.

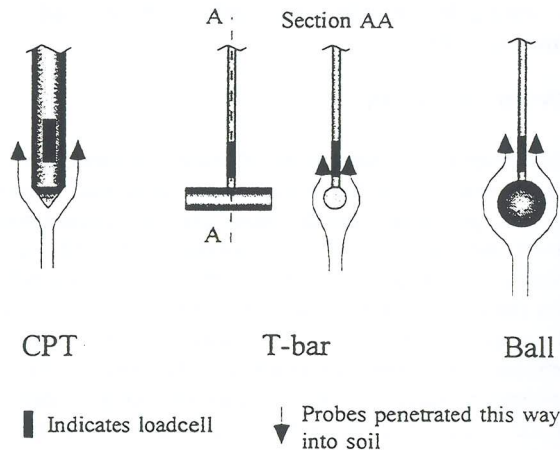


Figure 1 CPT, T-bar and ball penetrometer

As indicated in Figure 1, soil flows above the new probes during penetration, thus allowing equilibrium of the *insitu* vertical stress. Although a small correction is required for the area of the shaft in a similar manner to the CPT, no significant correction is required and the measured bearing pressure (q_m) is equivalent to the net bearing pressure (q_{net})

Thus q_m can be directly correlated to the undrained shear strength using

$$q_m = (N_{Ball} \text{ or } N_{T-bar}) s_u \quad (7)$$

where N_{T-bar} and N_{Ball} are factors derived from numerical analysis and experimental research. For the case of the T-bar, an exact solution was derived for N_{T-bar} by Randolph and Houlsby (6) using plasticity analysis, with values ranging from 9.14 for a fully smooth analysis to 11.94 for a fully rough case. In this project an intermediate value of 10.5 has been adopted, with support for this coming from Stewart and Randolph (7) where results were reported from field tests of a prototype scale T-bar penetrometer, and a value of 10.5 was proposed.

In the case of the ball penetrometer, disagreement exists between current numerical solutions and experimentally derived values. A value of 10.5 is recommended, and this is further discussed in Watson et al (8).

As will be demonstrated in section 5.2, the T-bar and ball penetrometer provide alternative means of estimating monotonic undrained shear strength. Although the tests have been conducted using model probes under centrifuge test conditions, it is expected that the results would be equally valid under field conditions, with testing currently ongoing to examine this further.

4 ROTARY ACTUATOR

As mentioned previously, a new device was developed as part of this research program. The new apparatus (referred to as the *rotary actuator*) can be used for traditional vane shear tests in flight in the centrifuge, but has primarily been developed to accommodate the new Torsional Plate Load Test (TPLT) discussed below. With the exception of some specific components, the entire actuator was designed and constructed at the Department of Civil Engineering at UWA. A description of the equipment and its features is now presented.

4.1 General Description

Illustrated in Figure 2, the rotary actuator is designed to be housed within existing actuators on the centrifuge, and is supported using clamps (I). The existing actuators enable vertical and lateral movement of the foundation or probe, while torsion (and thus rotation) is applied using the new apparatus.

Torque is applied to the foundation (or probe) using a Motor-Tacho-Gearbox combination (A) purchased from Portescap[®] to design specifications. Having a mass of less than 500 g (note that weight is an important factor in the design of all equipment on the centrifuge), the inline system utilises at 100:1 gear ratio to provide up to 10 Nm of torque at rotation speeds up to 1 rev/s. A flexible coupling (B) links the gearbox with the lead shaft (C), which also supports a purpose designed and built slip ring assembly (D).

Specially designed within an insulated cell, the slip ring passes the analog signal from load cells located just above the soil probes (see section 4.2) during continuous rotation, thus eliminating the need for cables located along the shaft. Power for the motor and tachometer feedback for velocity control during testing, as well as signals from the load cells and encoder (see below) are passed through a single connection (J), which is connected to a patch box which distributes the various signals for processing and data acquisition.

A detachable connection (E) is located at the base of the lead shaft, which allows multiple shaft extensions to be connected to the apparatus, and a variety of foundation types to be tested. Axial load generated during penetration is prevented from reaching the slip ring / motor assembly by passing the lead shaft through two angular contact bearings (F).

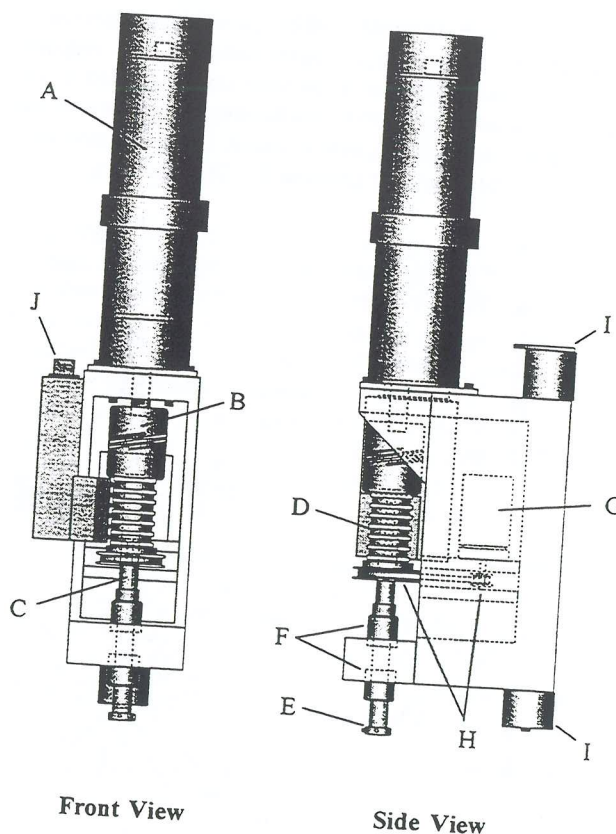


Figure 2 Rotary actuator

Position and velocity is measured using an encoder (G) coupled to the lead shaft via a 4:1 flexible gear and pulley system (H). The encoder signal (consisting of three out-of-phase signals) is processed using electronics developed at UWA, and produces output for rotation and angular velocity during continuous rotation. Sensitivity of the encoder signal is rated at 0.094 deg/bit for rotation angle and 0.1696 deg/s/bit for angular velocity, giving precision control over both position and velocity defined loading events.

The entire apparatus is housed within a clear perspex shield (not illustrated in Figure 2), which provides protection for the various internal components.

4.2 Foundation Types

At present two types of foundation / probes are being examined using the apparatus. These are illustrated in Figure 3, and are the vane and TPLT apparatus.

Compared to those used *insitu*, the vane fabricated at UWA is somewhat squatter in profile, with an aspect ratio ($=h/d$) of 2/3. This maximises the number of tests that can be done in a centrifuge sample that is only 200 - 250 mm high, and to minimise the effect of strength gradient on observed results. However, the geometry of the vane has a significant influence on the results obtained (discussed further in Section 5.1).

The TPLT consists of a model foundation 30 mm in diameter with skirts 10 % of the diameter. The TPLT can be used to predict the monotonic undrained shear strength of the soil

either through back analysis of the penetration response of the foundation, or through an examination of the response to torsional loading (similar to the vane test, discussed in Section 5.3.1). In addition, the cyclic behaviour of the soil can be examined by applying cyclic loads to the foundation and observing the behaviour (Section 5.3.2).

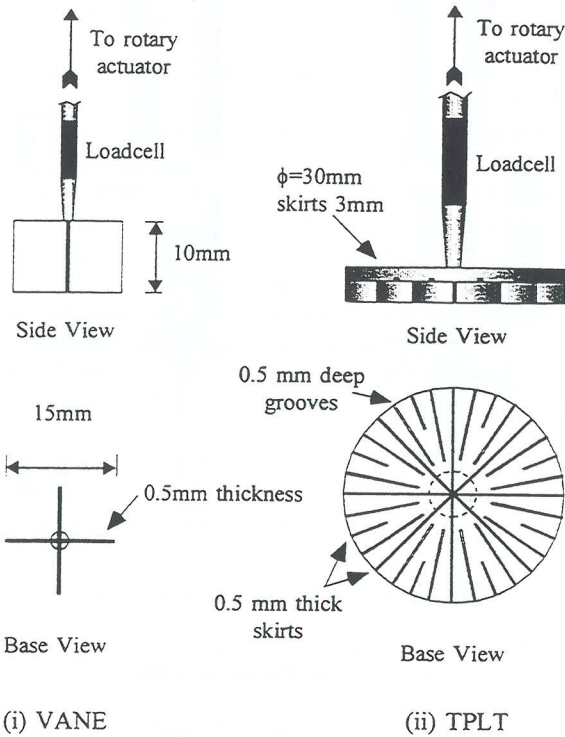


Figure 3 Rotary actuator foundation / probe devices

4.3 Software Development

In addition to the various mechanical components, a full complement of electronic equipment and computer software has been developed to support the rotary actuator.

At present the software (written in QuickBasic format) allows the following tests to be conducted :

- Mode 1** Standard vane shear test. This test mode involves rotation of the vane at a selected rate under torsion load and/or rotation limit control.
- Mode 2** Cyclic loading. This test mode allows the model foundation to be cycled between torsion limits while maintaining a chosen vertical stress. Limits are set on the rotation speed and the amount of rotation allowed.
- Mode 3** Sideswipe test. This test mode involves continuous one way rotation of the foundation under torsion load and/or rotation limit control. Prior to rotation a selected vertical stress is achieved, and the rotation is carried out under conditions of zero vertical strain.
- Mode 4** Probe test. This test mode involves continuous one way rotation of the foundation under torsion load and/or rotation limit control. Prior to rotation a selected vertical stress is achieved, which is maintained during rotation.

Test modes 2-4 are designed to be used with the TPLT apparatus, with mode 2 being used to investigate the cyclic behaviour of the foundation, and mode 3 and mode 4 being used to investigate the relationship between torsional load and vertical stress.

5 RESULTS

5.1 Vane Shear Tests

As mentioned previously, CPT, T-bar and ball penetrometer tests have been conducted in calcareous clay at 120 g. In addition, vane tests have been conducted in the same calcareous clay to provide a direct comparison of undrained shear strength deduced from the various test devices.

Figure 4 presents the results obtained from vane tests at increasing depth in the calcareous clay. At each depth the vane was rotated at a constant velocity of 12 deg/s, with a wait time of 30 seconds after insertion of the vane prior to rotation. Although not discussed here, further research has shown that the effect of rotation rate and wait time on the observed undrained shear strength is minimal.

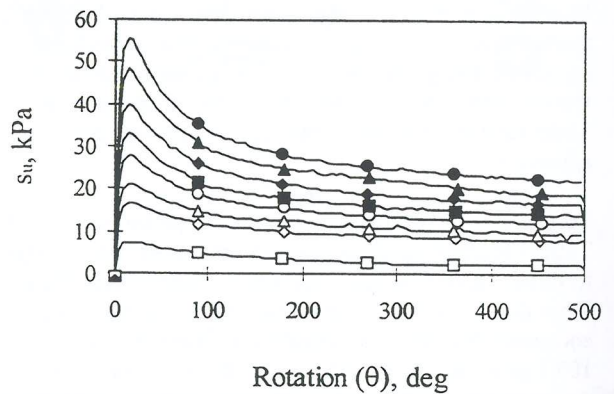
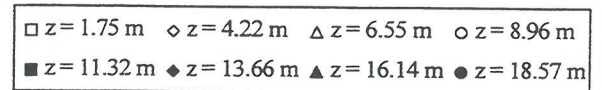


Figure 4 Example of vane testing in calcareous clay

As can be seen from the figure, a peak is observed after approximately 15 degrees rotation, followed by considerable strain softening. Although the results are presented as undrained shear strength, a direct comparison with CPT, T-bar and ball penetrometer results indicated that the observed vane results were approximately 20 % higher. Possible reasons for this are explained in more detail in Watson et al (8), and relate to the geometry of the model vane and soil strength anisotropy. Factoring the results by 83 % provides an excellent fit with the other test devices (see Section 5.2). This is recommended as the vane factor for the UWA vane, and is supported by tests conducted in several other soil types.

5.2 Comparison of s_u

Figure 5 presents a comparison of s_u profiles for the calcareous clay using the various devices. In the analysis it was assumed that $N_{T-bar} = N_{Ball} = 10.5$, and that $N_{CPT} = 11$. In addition it was determined that for processing the CPT data :

$\sigma_v \sim 15 \text{ kPa/m}$ (from water contents determined at the end on testing), $\alpha = 13 \%$ (determined from laboratory calibration) and $\beta = 1.0$ (based on experience with similar materials). The vane results have been factored by 83 % as explained in section 5.1.

$$\frac{kD}{s_{uo}} = \frac{D}{d} \quad (9)$$

From this a continuous profile of N_c can be determined from the Hously and Wroth solutions for the range of D/d occurring during penetration of the TPLT.

Note that the above analysis assumes an infinitely thin footing, and a correction has been made to N_c to allow for side shear acting over the full depth of the TPLT. Assuming a fixed percentage of the soil shear strength (δs_u) at the plate/soil interface and 100 % of s_u where there is soil/soil shearing, this amounts to adding roughly 0.5 to the value of N_c deduced using the original Hously and Wroth solutions. Figure 6 shows the observed bearing response, and the deduced N_c relationship considering the TPLT to be a shallow footing.

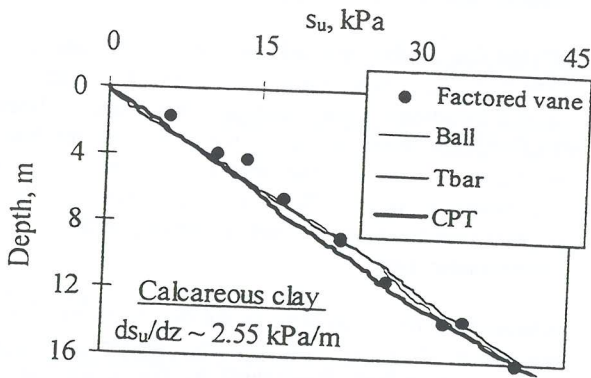


Figure 5 Comparison of s_u profiles from various test devices

As can be seen, an excellent comparison can be made between the various test devices in estimating the undrained shear strength of calcareous clay in the centrifuge.

5.3 Torsional Plate Load Tests

As previously mentioned, the TPLT can be used as a tool for investigating both the monotonic and cyclic properties of a soil.

5.3.1 Monotonic loading

The monotonic shear strength of the soil can be determined from either the penetration response of the TPLT, or from an examination of the torsional response generated by rotating the foundation at depth (similar to the vane).

Since soil flows above the TPLT (similar to the T-bar and ball penetrometers), no correction is required for overburden pressure and the net bearing pressure is equal to the measured bearing pressure (q). The measured bearing pressure can then be used to generate an s_u profile using

$$s_u = q/N_c \quad (8)$$

where N_c is the bearing capacity factor. By considering the TPLT as a shallow foundation bearing on the surface of soil with strength varying linearly with depth, a profile of N_c can be determined from solutions presented in Hously and Wroth (9).

Hously and Wroth deduced that for surface footings bearing on soil with strength proportional to depth such that $s_u = kd$ (where k is the strength increase per metre and d is the depth below the foundation), the bearing capacity factor is a function of the ratio kD/s_{uo} (where s_{uo} is the undrained shear strength at the soil surface and D is the foundation diameter). By excluding depth effects and considering s_{uo} as being the shear strength at the depth of the TPLT during penetration, it can be shown that

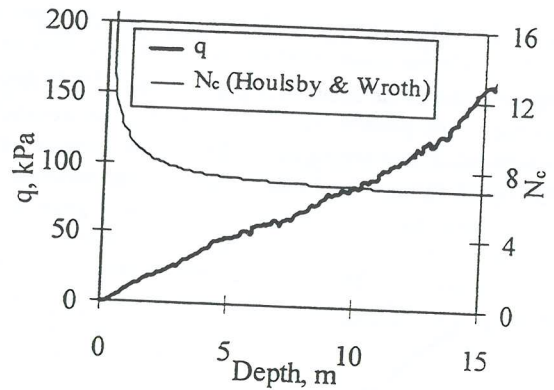


Figure 6 q and N_c

However, as indicated the above analysis ignores the effect of embedment on the foundation response. As such, bearing capacity factors determined using the above method are likely to significantly underestimate the bearing capacity at high embedment. Using a constant value of N_c for the full penetration (similar to that used for the penetrometer devices outlined above) can also be used, and a comparison is made using a constant value of N_c equal to 10.5.

To deduce shear strength from the torsion response, a similar expression is used to that applied to the vane test. However, allowance must be made for shear along the top plate. The equation used to deduce s_u from rotation of the TPLT at depth was

$$s_u = \frac{T}{2\pi^2(r/3 + r\delta/3 + t\delta + h)} \quad (10)$$

where T is the measured torque, t is the thickness of the top cap, h is the skirt height, r is the radius of the TPLT and δ a defined above for monotonic penetration of the TPLT. An average shear strength is assumed to act over the TPLT depth.

Figure 7 presents results obtained using the TPLT apparatus to deduce shear strength in calcareous silt at 150 g. As can be seen, good agreement exists between the shear strength deduced from the monotonic push (using $N_c = 10.5$) and the torsion results (using $\delta = 0.4$). The shear strength obtained using the bearing capacity factors shown in Figure 6 is

significantly higher, and use of a constant value of 10.5 is recommended.

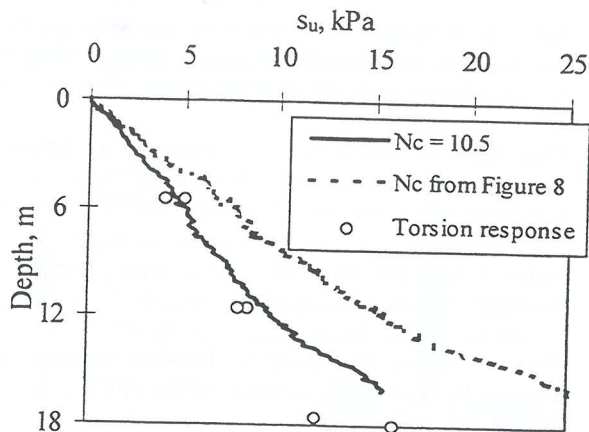


Figure 7 Monotonic s_u from TPLT tests

Figure 8 shows the shear strength profiles derived from TPLT testing in comparison with T-bar and ball penetrometer tests conducted in calcareous silt. As can be seen, an excellent agreement exists between the various testing methods.

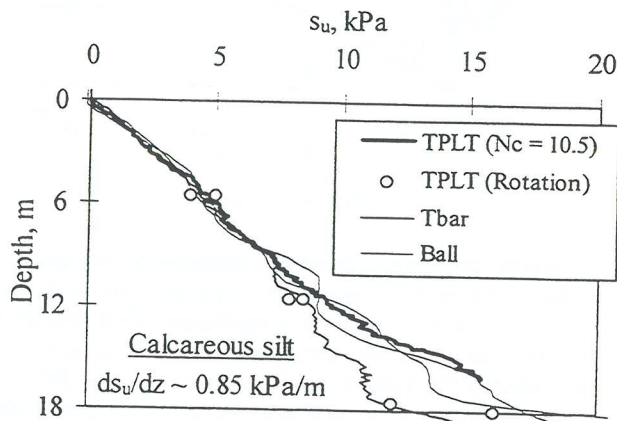


Figure 8 s_u profiles from various tests

5.3.2 Cyclic loading

In addition to the monotonic shear strength, TPLT testing can be used to investigate the cyclic performance of soils. Although only in the preliminary stage, it is hoped that cyclic torsional loading (T_{cyc}) about an average torsion load (T_a), applied at different levels of constant vertical stress (V_a), will provide insight into the behaviour of real foundations subjected to cyclic loading induced by wave or storm loading.

6 CONCLUSIONS

Results have been presented from inflight centrifuge testing of two calcareous materials typical of soil types found on the North-West Shelf of Western Australia. The focus of the work has been directed toward the development of alternative soil testing apparatus to overcome shortcomings associated with the existing *insitu* testing devices for the centrifuge.

T-bar and ball penetrometer testing has been shown to provide results comparable with CPT results, but which can be obtained without the corrections for excess pore pressure and *insitu* stress required to process the CPT data. The results are supported by inflight vane testing using the new rotary actuator described in detail in this paper.

A new test device, named the Torsional Plate Load Test (TPLT) has also been introduced. The TPLT can be used to predict monotonic shear strength either from analysis of the load response observed during penetration of the foundation, or from analysis of the torque required to rotate the foundation at depth. Both methods have been shown to produce results which compare favourably with T-bar and ball penetrometer tests.

Although the focus has been on the development of laboratory equipment, it is expected that the results will have field applications as well, highlighted by the recent use of T-bar testing apparatus at an offshore site in the Timor Sea.

7 ACKNOWLEDGEMENTS

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