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Laboratory measurement of strength of weak clay samples

Mesure en laboratoire de la résistance des échantillons d'argile faible

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ABSTRACT: The use of Triaxial tests to directly measure the undrained shear strength of very soft clays is impractical due to resulting sample disturbance and provides inadequate resolution. Indirect testing methods including the fall cone, T-bar and cone penetrometer test (CPT) are often preferable. However, analysis of these methods is dependent on empirically derived correlations. Variable bearing capacity factors derived from large scale tests or from in-situ testing introduce uncertainty concerning results of penetrometer tests. A robust, simple and reliable method of determining the undrained shear strength of very soft clays is required. Miniature T-bar and cone penetrometers were developed for this research. Experiments were conducted to measure the resistance to penetration in Speswhite Kaolin and Bentonite clay samples, with strengths ranging from approximately 1kPa to 20kPa. The effects of moisture content and rate of penetration were investigated. Results from penetrometer tests and standard fall cone tests were compared to determine suitable bearing capacity factors, to enable estimation of the strength of samples tested in relation to moisture content.

RÉSUMÉ: L'utilisation d'essais triaxiaux pour mesurer directement la résistance au cisaillement non drainé d'argiles très molles n'est pas pratique en raison de la perturbation résultante de l'échantillon et fournit une résolution inadéquate. Les méthodes de test indirectes, notamment le test du cône d'automne, du test en T et du pénétromètre à cône (CPT), sont souvent préférables. Cependant, l'analyse de ces méthodes dépend de corrélations empiriquement dérivées. Les facteurs de capacité portante variables dérivés d'essais à grande échelle ou d'essais in situ introduisent une incertitude concernant les résultats des essais au pénétromètre. Une méthode robuste, simple et fiable pour déterminer la résistance au cisaillement non drainé d'argiles très molles est nécessaire. Des pénétromètres à cône et à cône miniatures ont été développés pour cette recherche. Des expériences ont été menées pour mesurer la résistance à la pénétration dans des échantillons d'argile Speswhite Kaolin et Bentonite, avec des forces allant d'environ 1 kPa à 20 kPa. Les effets de la teneur en eau et du taux de pénétration ont été étudiés. Les résultats des tests au pénétromètre et des tests au cône de chute standard ont été comparés afin de déterminer des facteurs de portance appropriés, afin de permettre l'estimation de la résistance des échantillons testés par rapport à la teneur en humidité.

Keywords: CPT; T-bar; undrained shear strength; weak clay; bearing capacity

1 INTRODUCTION

The robust and reliable measurement of the undrained shear strength of weak clays for use in laboratory model and centrifuge tests is a challenging task. Element testing, such as the undrained triaxial test, is often impractical due to the disturbance resulting from sampling and handling of the soil samples. The use of indirect testing methods, such as the T-bar and cone penetration test, avoids such pitfalls and is often deemed preferable (Randolph and Houlsby, 1984; Oung et al. 2004). These methods allow the determination of shear strength variation over short depths while being of rapid execution. Analysis of these methods is dependent on empirically derived correlations. There is often uncertainty regarding appropriate values of empirical factors (Stewart and Randolph 1994), and their reliability for use with smaller scale laboratory penetration tests requires further exploration.

This research focusses on laboratory testing of clays with extremely low (<10kPa) to very low (10-20kPa) remoulded undrained shear strengths, according to BS EN ISO 14688-2. Index tests were undertaken on speswhite kaolin and bentonite clays, to define the range over which the clays are plastic and to estimate undrained shear strengths. These strengths were correlated with resistances measured in both clays using T-bar and cone penetrometers - in order to: (i) derive empirical factors for the conversion of penetrometer resistance for these two materials under very low stress levels in small scale laboratory tests (ii) compare such factors with already published studies (iii) investigate the effect of penetration rate and soil moisture content.

2 LABORATORY MEASUREMENT OF UNDRAINED SHEAR STRENGTH

During loading of clays undrained conditions are customarily assumed in the short term. Undrained conditions are assumed where water is not able to flow freely in or out of the soil element during loading, or if the permeability is sufficiently low.

There are a number of factors which affect the undrained shear strength of clays, these include the nature of soil grains, geological history, orientation of stresses, degree of saturation and rate of shearing. Undrained shear strength is normally determined from a combination of laboratory shear strength tests and in-situ testing.

2.1 Index Parameter Testing

Empirical correlations can be obtained between index properties and strength and compressibility using critical state soil mechanics.

2.1.1 Fall Cone Testing

The fall cone test provides fast measurements and is portable and simple to use. Undrained shear strength, *Cu* (kPa), is a function of the cone angle, α, cone factor, *K*, the penetration of the cone at rest, *d*, mass of the cone and shaft, *m*, and acceleration due to gravity, *g*, taken as 9.81, (Muir Wood 1990).

$$Cu = \frac{K_{\propto}.m.g}{d^2} \tag{1}$$

The standard British fall cone has a 30 degrees apex angle and mass of 80g, (BS 1377, 1990). The roughness of the cone has the most significant impact on the value of the strength obtained at the liquid limit, (Houlsby 1982). The cone therefore needs to be as smooth as possible. The suggested cone factor for the standard 30 degrees cone is 0.85 (Muir Wood 1985).

Undrained conditions can be assumed due to the rapid penetration of the cone, (Koumoto and Houlsby 2001). Sensitivity is not taken into account for remoulded soils. It is therefore not possible to establish any loss of undrained strength with shear strain. Heave of the soil around the cone is also unaccounted for, which will influence the load on the cone, (Houlsby 1982). Calculations assume the soil surface to be flat. The resulting calculated strength is therefore an overestimate, (Houlsby 1982). As such a small proportion is being sampled the reliability of these results is questionable, (Stone and Phan 1995).

2.1.2 Thread Rolling Test

The plastic limit, W_P, corresponds to the water content at which a 3mm diameter thread of soil begins to shear transversely and longitudinally, (BS 1377-2:1990).

2.2 Penetration Tests

Various types of penetrometer can be used to estimate the undrained shear strength of soils by applying empirical relationships.

2.2.1 Cone Penetration Test (CPT)

Laboratory strength testing has utilised miniature cone penetrometers. Oung et al. (2004), used cones with diameters of 6.47mm and 7mm, with a 60 degrees tip, and penetration rates of 0.05mm/sec, 0.5mm/sec and 5mm/sec.

In comparison, the in-situ cone penetration test apparatus consists of a cylindrical penetrometer attached to a 37.5mm diameter cone. In-situ testing involves pushing the penetrometer directly into the ground at 20mm/sec by static thrust. The resistance to penetration is measured by a load cell just behind the cone tip. The force due to side friction immediately above the cone is measured using a slightly roughened friction sleeve mounted on strain gauged supports to obtain continuous readings. The measured cone resistance is very small in soft deposits. The accuracy of readings taken in very soft soils is therefore difficult to determine and results may be unreliable.

The undrained shear strength of the soil, *Cu* (kPa), is defined as the ratio of the measured cone resistance, q_c (kPa), and the bearing capacity factor, N_c, (Stewart and Randolph 1994).

$$Cu = \frac{q_c}{N_c} \tag{2}$$

For in-situ testing a bearing capacity factor N_c of 15 is typically used, as suggested by Oung et al. (2004) and results from comparisons with the vane test. The bearing capacity factor depends on site conditions such as soil stiffness, stress level and stress history. The bearing capacity factor is to be determined for the miniature CPT.

The cone penetration test provides a continuous measurement of undrained shear strength. Soil failure is by means of asymmetric deformation in the vertical plane around the cone during penetration as cavity expansion is caused ahead of the penetrometer, therefore corrections for overburden pressures and pore pressures are required. The piezocone is a variation of the cone penetrometer and incorporates a piezometer consisting of a porous tip and pressure transducer to measure pore water pressures generated during penetration. This enables a correction to be applied to the measured tip resistance, to take into account excess pore water pressure at the tip of the penetrometer. For smaller scale laboratory testing it may not be possible to incorporate a water pressure transducer due to lack of space in the shaft.

2.2.2 T-Bar Test

The small-scale laboratory T-bar full flow penetrometer was first introduced by Stewart and Randolph at UWA in 1991 to obtain an estimate of the shear strength profile of clay samples tested in a centrifuge. The device comprised a 20mm long, 5mm diameter cylinder attached perpendicularly to a conventional cone penetrometer, (Stewart and Randolph 1994). The surface of the cylinder was roughened by sand blasting and the ends machined smooth. The T-bar was pushed into the soil at the same rate as for a conventional cone penetration test while the measurement of resistance to flow of soil around the T-bar was measured by a load cell. As the penetration force is much higher than that used for cone penetration testing errors due to area correction as a result of excess pore pressures are much less significant. There is not a standard size of T-bar; Oung et al. (2004) used a T-bar with a 7.08mm diameter, 30.11mm long cylinder and 6.47mm diameter shaft.

T-Bar testing enables a continuous profile of undrained shear strength to be obtained and no corrections are required for effects of pore water pressure. Oung et Al. (2004) found that water pressure had little effect on T-bar measurements.

Plasticity analysis can be used to obtain values for undrained shear strength, *Cu* (kPa), from measurements of resistance of the clay to penetrometer movement, (Randolph and Houlsby, 1984).

$$Cu = \frac{P}{N_b.d} \tag{3}$$

A value of 10.5 is recommended for the empirical factor, N_b. *P* (kN) is the force per unit length along the T- bar head and d is the diameter of the T-bar cylinder.

Laboratory testing indicates that the T-bar bearing capacity factor is insensitive to stress level and stress history, (Stewart and Randolph 1994). The effect of the smooth ends of the T-bar are ignored in addition to the influence of the penetrometer shaft as this occupies a relatively small proportion of the projected cross-sectional area of the T-bar, (Stewart and Randolph 1994).

The T-shape penetrometer causes symmetrical deformation and flow in the plane perpendicular to the T-bar axis during penetration. In-situ vertical stress is equilibrated across the T-bar and no correction for overburden pressure is required, (Newson et al. 2004). Bar lengths of 4 to 5 diameters are typically used, to avoid instability of the T-bar and non- uniform resistance, (Newson et al. 2004).

3 ANALYTICAL METHODS

3.1 Cone penetration test: driven piles

The cone penetration test can serve as a small-scale model test for a driven pile, as shown in Figure 1 (a). This enables the shaft resistance to be determined.

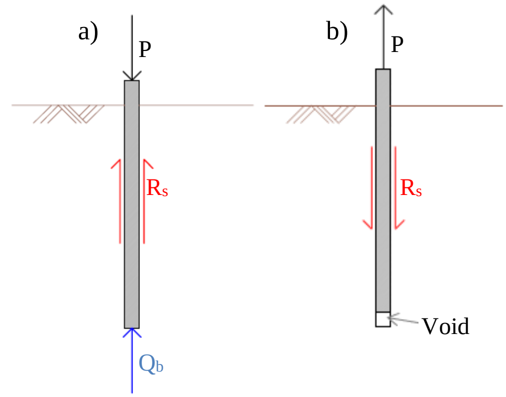

Figure 1: Forces acting on a pile during driving into clay (a) and pile pull-out (b)

$$P = Q_b + R_s \tag{4}$$

The ultimate resistance, *P* (kN), of a single pile in clay, is the sum of the base resistance, Q_b (kN), and the shaft resistance, R_s (kN), of the section of pile in contact with the clay soil.

The base resistance is a function of the projected area of the base of the pile, A_b (m^2), bearing capacity factor, N_c, and the undrained shear strength at the base of the pile, Cu_b (kPa), (Tomlinson 1975).

$$Q_b = N_c.Cu_b.A_b \tag{5}$$

Experience offshore has shown that there is a close correlation between end bearing of the cone penetrometer and the end resistance that develops at the tip of a pile during driving, (Norris and Holtz 1981). Shaft friction can be obtained from pull-out tests. As the pile is pulled out the shaft friction reverses direction and R_s becomes negative, as shown in Figure 1 (b).

Resistance to pull-out of piles results from skin friction between the pile and soil and suction generated at the base of the pile as this moves out of the soil and creates a void, (Madabhushi and Haigh 1998). Undrained shearing occurs along the side of the pile as it is pulled out.

3.2 T-bar test: plasticity analysis

The results of T-bar tests can be interpreted using the plasticity solution for the limiting pressure acting on a cylinder moving laterally through a cohesive soil, (Stewart and Randolph 1994). The force per unit length acting on the T-bar cylinder, P, is the ratio of the measured base resistance, Q_b, and length of the cylinder. Therefore Eq. (3) can also be written as follows, where A_b is the projected area of the T-bar cylinder.

$$Cu = \frac{Q_b}{N_b.A_b} \tag{6}$$

The bearing capacity factor depends on the roughness of the T-bar cylinder and varies between 9.14 and 11.94 for a fully rough cylinder; a value of 10.5 is recommended, (Randolph and Houlsby 1984). It is assumed that soil flow around the bar is plane strain and closes fully behind the bar, with the exception of small regions around the vertical shaft, (Newson et al. 2004).

4 MATERIALS AND METHODOLOGY

4.1 Materials

Two clay types were tested, speswhite kaolin and bentonite. The majority of clays formed by sedimentation are mixtures of kaolinite and illite, with varying amounts of montmorillonite. Kaolinite has strong interlayer hydrogen bonds and low shrinkage and swelling properties, with particles up to 4μm long. Bentonite is a type of montmorillonite and contains small, thin particles of 1 to 2 μm in length to which water is readily attracted, resulting in high susceptibility to expansion, swelling and shrinkage. Layers of montmorrilonite are held together by weak Van der Waals forces and are easily separated by adsorption of water. Properties of the bentonite powder (Berkbent 163) used in this research are detailed in Table 1, as provided by Tolsa UK.

Property	Value
Composition by weight	>98% Bentonite <2% Sodium Carbonate
Moisture content	10-14%
Specific Gravity	2.7

Table 1: Properties of Berkbent 163

This is a fast hydrating civil engineering grade bentonite, designed for diaphragm walling and piling. Bentonite suspensions, typically containing around 5% by mass of water, are used to support boreholes and trench excavations prior to being filled with concrete to form piles and retaining walls.

4.2 Sample preparation

The clay powder was weighed, and the required mass of water calculated to produce samples of specific moisture contents. After mixing, samples were wrapped in cling film and placed in a sealed bag, to ensure moisture was retained. Samples were remoulded every few days to help produce a homogeneous sample for testing. The prepared clay samples were kept in a cold store when not in use. Bentonite samples were left for a week before testing to help ensure even distribution of moisture. The clay was not consolidated.

4.3 Fall cone and thread rolling tests

Fall cone tests were undertaken in accordance with BS 1377: 1990. Eight samples of kaolin of moisture contents ranging from 40% to 75%, in 5% increments, were prepared for testing. The cone and shaft were cleaned and lightly oiled prior to each test to reduce frictional effects. Samples of clay from each test were weighed immediately after testing and again following at least 24 hours of drying at 105°C in order to determine the exact moisture content, w, from the ratio of the mass of water, Mw, to the mass of soil, Ms.

$$w = \frac{M_w}{M_s} \tag{7}$$

Fall cone testing was repeated using six samples of bentonite, prepared with moisture contents ranging from approximately 100% to 350% in 50% increments.

Thread rolling tests (BS 1377-2:1990) were undertaken to establish the plastic limits.

4.4 *Penetration Testing*

Miniature cone and T-bar penetrometer devices were designed and fabricated for this research, from solid aluminium and stainless-steel cylinders respectively, with dimensions as per Figure 2, and projected areas as per Table 2.

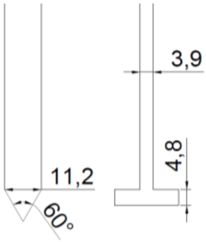

Figure 2: Penetrometers (dimensions in mm)

Penetrometer	Projected area (mm^2)
Cone	98.52
T-bar	93.22

Table 2: Projected area of penetrometers

The penetration testing utilised a Triaxial testing load frame, to which the penetrometers were clamped. 12kg capacity scales, with a resolution of 0.1g, were placed beneath the sample for use as a load cell. The cone penetrometer, clay sample and scales acted as a series of springs, therefore forces calculated from scale readings were the same as those exerted on the penetrometer and clay sample. Clay samples were compacted into a Proctor Mould of height 115mm and diameter 102mm.

The samples were raised at rates of 2mm/min and 5mm/min to investigate effects of rate of penetration. Tests were timed, and scale readings were taken manually every thirty seconds, the depth could be determined from the time and rate of loading. During loading, the resistance to the movement of the penetrometer through the clay was obtained via the scale reading, this was converted into a resistance in kN. When testing using the T-bar the shaft resistance is neglected, therefore readings were only taken for the loading stage. As the cone penetrometer reached a depth of approximately 95mm into the sample the loading was reversed, and scale readings taken as the cone penetrometer moved out of the clay to obtain values of shaft friction. During the loading stage both the tip and shaft of the cone penetrometer were in contact with the clay, hence resistance measured was the ultimate resistance.

Four samples of kaolin were prepared for testing, with moisture contents of approximately 45%, 55%, 65% and 80%. Four samples of bentonite were prepared of approximately 250%, 350%, 450% and 550% moisture content. Once testing was completed, small samples of clay were taken from the top, centre and base of the sample, weighed, and then dried for 24 hours in order to determine the average moisture content of the sample tested, using Eq. (7).

5 RESULTS

5.1 *Fall cone and thread rolling tests*

Liquid and plastic limits obtained, which determine the range over which the clays are plastic, are given in Table 3. Undrained shear strengths were obtained by empirical correlations, using Eq. (2) and a cone factor of 0.85. Shear strength trends with varying moisture content obtained for kaolin and bentonite are shown in Figures 4 and 5.

Clay	Liquid limit (%)	Plastic limit (%)
Kaolin	68.50	31.70
Bentonite	515.0	61.03

Table 3: Index properties

5.2 *Penetrometer Tests*

Bearing capacity analysis was used to estimate undrained shear strength from measured tip resistances, Q_b. Figure 3 shows a typical profile of resistances obtained using the cone and T-bar penetrometers.

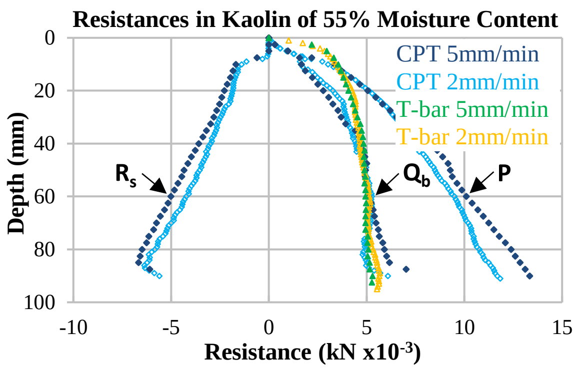

Figure 3: Resistances obtained for a kaolin sample

For the CPT, measured shaft resistances are negative due to being obtained during penetrometer removal, this therefore becomes a reverse bearing capacity problem, hence R_s is entered as a positive value when calculating Q_b from Eq. (4). T-bar tip resistances could be obtained directly. Using the calculated Q_b from the CPT, undrained shear strength is calculated using Eq. (5). Eq. (6) was used to calculate values of undrained shear strength from resistances measured using the T-bar.

5.2.1 Bearing Capacity Factors

To determine suitable bearing capacity factors for each penetration device used, a profile of moisture content in relation to strength was plotted for each clay type, as shown in Figures 4 and 5. To generate these profiles, average values for measured resistance were plotted using results obtained between 35mm and 70mm sample depths. This range was chosen as it corresponded to depths between which there was a good agreement between measured resistances for cone penetrometer and T-bar tests. Randolph and Houlsby (1984) deduced that for a pile in soft clay low resistance will be observed up to three diameters below ground level due to a wedge type failure in front of the pile. Three diameters of the cone penetrometer equate to 33.6mm.

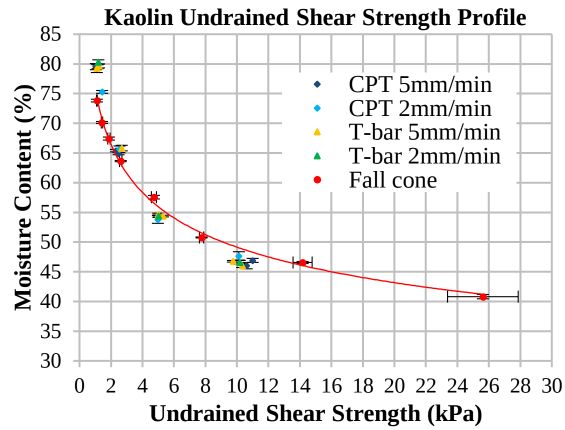

Figure 4: Kaolin undrained shear strengths

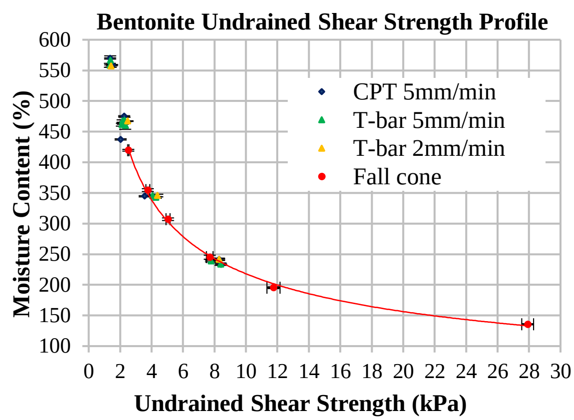

Figure 5: Bentonite undrained shear strengths

Once plots were formed bearing capacity factors N_c and N_b were adjusted until the best fit with fall cone results was achieved. Using a bearing capacity factor of 10.5, as recommended by Randolph and Houlsby (1984), resulted in a good fit between results for T-bar and fall cone tests. A bearing capacity factor of 10 was found to be suitable for the cone penetrometer. Oung et al. (2004) found that when a bearing capacity factor of 10 was applied to miniature cone penetrometer test results this resulted in a good fit with results they obtained using a T-bar.

Undrained shear strength was found to increase exponentially with decreasing moisture content. Stone and Kyambadde (2007) reported that an exponential relationship between strength and moisture content is considered appropriate.

The negligible effect of shearing rate can also be seen in figures 4 and 5.

6 CONCLUSIONS

The miniature T-bar and cone penetrometer devices and testing procedures developed were found to be suitable for obtaining the undrained shear strength of weak clay samples.

The rate of penetration was found to have an insignificant effect on values of undrained shear strength obtained. More inconsistencies in tip resistance were observed when using the lower rate of 2mm/min, the rate of 5mm/min was found to be the most appropriate in order to obtain reliable results. Moisture content had the most significant effect on undrained shear strength.

Tests undertaken showed that reliable results can be obtained using small 102mm diameter samples. Similar miniature T-bar testing undertaken by Levacher et al. (2016) in kaolin used samples of 300mm diameter.

Bearing capacity analysis was found to be appropriate for both T-bar and cone penetrometer tests, to obtain estimates of undrained shear strength using suitable bearing capacity factors. The bearing capacity factors found to be suitable in respect of T-bar and cone penetrometer laboratory tests are in agreement with values reported by Randolph and Houlsby (1984) and Oung et al. (2004) respectively, which adds confidence to these findings.

7 ACKNOWLEDGEMENTS

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