ABSTRACT

Determination of undrained shear strength $Su$ and sensitivity $St$ of soft soils and sediments are important in geotechnical design as well as in sediment management. Usually these properties are deduced from laboratory or field tests. In lab, vane shear test (VST) is commonly used in clayey soft soils. Other testing is available such as the full flow penetrometers mainly used for in situ offshore engineering and for centrifuge modeling applications. Among them, the T-bar test (TBT) is not really used in geotechnical lab at 1 g level in small layers of soft soils put in containers. This paper deals with measurement of undrained shear strength ($Su$) of soft clays (kaolin clay) and dam sediment under conditions of natural drying, consolidation and drainage, using two different methodologies, namely T-bar and vane shear tests.

Vane shear test is a standard test for $Su$ measurement but not applicable for obtaining a continuous profiling of $Su$ versus depth and it provides rather discrete measurements. Hence T-bar test has been used to observe a continuous phenomenon during shearing. Many studies have been reported comparing standard vane shear and T-bar tests to ensure applicability of the latter. Two different types of soils was tested to check the repetitiveness of testing and to validate previous works performed on $Su$ measurement of kaolin clay using T-bar tests.

Besides, in order to measure remolded shear strength, the vane is rapidly rotated through several revolutions until the clay becomes remolded. Again the same procedure is followed to measure the remolded shear strength. The ratio of two shear strengths measured (i.e. peak strength and remolded strength respectively) gives the sensitivity $St$. In addition to this, for comparative studies of TBT and VST, the methodology involves the rotation of vane blade 90 degrees anticlockwise and then 90 degrees clockwise. Although, this method is not usually used for VST testing, it enables to compare $Su$ measured in anticlockwise rotation with the downward movement of T-bar. Likewise, $Su$ is measured during clockwise rotation with the upward movement of T-Bar. In order to obtain compatibility between measurements made with T-bar and vane shear tests, it is interesting to study the ratio of measurements made by both tests. So, in order to do that, the peak value of each curve from vane shear test is compared with the average value of $Su$ measured by T-bar test along the depth of blade insertion. This practice is appropriate for comparison because $Su$ has been assumed as uniformly distributed over the entire height of the vane. So, in order to test the suitability of the comparison, the above practice is followed for all tests in kaolin clay and dam sediments. But still, it was interesting to observe the average of the ratios measured by different numbers of tests in kaolin and dam sediments and to compare them in order to see the applicability of the tests for different types of soils. So, average values of ratio ($r$, $r = Su (VST)/Su (TBT)$ are proposed. All test results are reported and discussed in the paper and conclusions are given.

Keywords: undrained shear strength, laboratory testing, vane shear test, T-bar test, soft soils, kaolin clay, dam natural sediment, residual undrained shear strength, measurements.
T-bar test TBT, (Yafrate, 2007; Levacher et al, 2014). The latter is commonly used in offshore engineering and centrifuge modelling, see table 1.

Table 1. Laboratory and in situ methods for Su measurement.

<table>
<thead>
<tr>
<th>Test type</th>
<th>Tip shape or probe</th>
<th>Su profile</th>
<th>Su identification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vane Shear Test</td>
<td>4 blades</td>
<td>discontinuous vs depth</td>
<td>direct</td>
</tr>
<tr>
<td>Ball Penetrometer Test - BPT</td>
<td>sphere</td>
<td>continuous vs depth</td>
<td>Nγ - factor + corrections</td>
</tr>
<tr>
<td>T-bar TBT</td>
<td>horizontal cylinder</td>
<td>continuous vs depth</td>
<td>Nγ - factor + corrections</td>
</tr>
</tbody>
</table>

The VST test provides Su profiles versus depth from discrete measurements either in laboratory or in field. Full flow penetrometers FFPT have the ability to give a continuous Su profile. They are considered as FFPT because the soil during deformation flows according the shape of the probes driven into soil during penetration and pulling out. The use in laboratory of T-bar penetrometers TBT have been originally developed in centrifuge centres. Recently, they have been adapted in some geotechnical departments for characterisation of very soft soils i.e. fine soils with high water content as dredged sediments. Considering VST, another advantage in using FFPT consists in the ability to obtain measurements during penetration (PE) and pulling out (PO), and to perform (PE-PO) cycles. Note that after the first penetration, TBT extraction is run into disturbed soil. Conditions of TBT laboratory use in small soft soils layers have been investigated recently (Cherifi, 2013; Dosso, 2013, Levacher et al, 2014). To compare both VST and TBT testing procedures and the results obtained in soft soils for characterization and Su determination, a research work was undertaken by Gupta (2013). The program deals with measurements of undrained shear strength (Su) of soft clays: a kaolin clay (KC) and a dam sediment (DS). KC is soft white homogenous clay, also called China clay. In its natural state it is a white soft powder. DS sample was already available in moist state from dredging site. Both samples have been prepared at 2 x LL of each soil so as to make it fall in soft soil range having very small Su values. Initial water content WCi was 103% and 88% respectively for KC and DS soils.

2 MATERIALS AND METHODS

Kaolin clay (KC) and dam sediment (DS) have been used as materials for the studies. A brief recap of their properties (see table 2) and preparation are given below, see table 3.

2.1 Kaolin clay and dam sediment

Two types of soft soils have been used for measuring undrained shear strength, namely kaolin clay (KC) and dam sediment (DS). KC is soft white homogenous clay, also called China clay. In its natural state it is a white soft powder. DS sample was already available in moist state from dredging site. Both samples have been prepared at 2 x LL of each soil so as to make it fall in soft soil range having very small Su values. Initial water content WCi was 103% and 88% respectively for KC and DS soils.

Table 2. Properties of kaolin clay and dam sediment.

<table>
<thead>
<tr>
<th>Property</th>
<th>KC clay</th>
<th>DS sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquidity limit LL</td>
<td>51.5</td>
<td>43.9</td>
</tr>
<tr>
<td>Pasticity limit PL</td>
<td>30</td>
<td>29.8</td>
</tr>
<tr>
<td>Grain size distribution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; 2 μm</td>
<td>79</td>
<td>21.2</td>
</tr>
<tr>
<td>2 μm - 20 μm</td>
<td>21</td>
<td>62.1</td>
</tr>
<tr>
<td>20 μm - 50 μm</td>
<td>-</td>
<td>16.6</td>
</tr>
<tr>
<td>50 μm - 200 μm</td>
<td>-</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Preparation consists in mixing fine soils and water so as to get a homogeneous paste, filling the cell for shear testing and making initial measurements (height of soil placed in the cell h0, mass of soil in the cell m0, initial water content WCi, and further Su measurements with both methods) at a reference time t0. Each soil layer is deposited on a geotextile posed at the bottom of the cell. A drainage system is installed around the cells with plastic bottles to collect water vs time. Two cells (same geometry), namely K5 and K6 respectively for KC and DS soils were used for testing, see figure 1.

![Cell plus geotextile at bottom](image1)

![Fine soil mixing](image2)

![Cell filling](image3)

![Fine soil layer before Su testing](image4)

Fig. 1. Steps of soil and cell preparation – case of DS soil.
2.2 Consolidation measurements

Settlement and drainage were measured to explain consolidation process of both soil samples every day. Settlement was measured by taking the average of four direct readings taken at four fixed positions of the cell. Drainage was measured by taking mass measurement of the drainage bottle connected to each cell. A strategy was adopted to obtain water content profile along the depth by using a plastic straw and by applying suction pressure, see upper right photo in figure 2. The value of measured water content by each segment of straw (i.e. total height was divided into 4 equal lengths noted from the top to the bottom: \( H, M_H, M_B, B \)) is used to obtain the water content profile by assigning measured value by each segment to a certain depth and then using curve fitting tool for profile. In order to measure the water content of each segment of straw, a lyophilizer has been used. Four small bottles are identified and after measurement of all required masses (i.e. empty mass of bottle and moist mass of soil); bottles are placed in lyophilizer for drying of samples.

2.3 Vane shear test apparatus

Vane shear test VST is basically a standard test for Su measurement in laboratory as well as in field in fine soils. The miniature VST is equipped with electrical torque transducer. Considering the procedure, the vane shear test consists in inserting a four-bladed vane in a soil specimen under testing and rotating it at a constant rate to determine the torque required to cause a cylindrical surface sheared by the vane. A 30mmx30mm vane blade has been chosen as it is best suited to present studies, thus satisfying guidelines given by ASTM D-4648-00; see figure 3. This torque is then converted to a unit shearing resistance of the cylindrical surface area. After measuring the torque, in order to determine Su, the following formula is used. In this approach, it is assumed that Su is uniform along the height \( h \) of the vane as well as the two circular top and bottom surfaces with vane diameter \( d \). The equation (1) establishes the relation giving Su versus the torque \( T \):

\[
Su = \frac{2T}{\pi d^2 (h + d/3)}
\]  

(1)

\[
Su = \frac{F_v}{(NTBT D L)} \text{ or } Su = \frac{P}{NTBT D}
\]  

(2)

where \( D \) and \( L \) are bar diameter and length respectively, \( NTBT \) is T-bar factor when the bar is totally embedded. Equation 2 can be also written using \( P \) as measured penetration resistance per unit length acting on the cylinder. From literature, values of \( NTBT \) are recommended for practice, they depend on the roughness of the bar, see table 3.

Table 3. Some proposed \( NTBT \) factor values.

<table>
<thead>
<tr>
<th>Roughness</th>
<th>Smooth</th>
<th>( a = 0.43 )</th>
<th>Rough</th>
</tr>
</thead>
<tbody>
<tr>
<td>( NTBT ) factor</td>
<td>9.1-9.2</td>
<td>10.5</td>
<td>11.9-12</td>
</tr>
</tbody>
</table>

An average recommended value for \( NTBT \) is 10.5 in deep penetration conditions corresponding to a friction
of 0.45 that represents a steel/soil interface. $N_{TBT}$ considered in this study was 9.2.

3 RESULTS AND DISCUSSION

3.1 Mechanism of T-Bar test

It is well-known that the undrained shear strength of soft clays increases linearly with depth (De Jong, 2011). Hence an ideal T-Bar test is expected to show a linear variation with depth. But it can be clearly observed from the results of T-bar test. However, $S_u$ is increasing with depth but it is happening in a nonlinear way. So, in order to have a better understanding for analysis, the results obtained are divided into 6 zones discussed below, see figure 4.

![Fig. 4. A T-bar test cycle in DS cell with water content profile.](image)

A possible explanation of each zone is as follows: (i) a foundation effect, showing a sudden increase in the beginning of each test where the magnitude is increasing as soil is pushing away. This is observed from 10 to 20 mm from surface either 1 to 2 diameter of T-bar,

(ii) a regular trend, with complete development of full flow around the T-bar where $S_u$ measured evolves as expected with little variations due to water content profile,

(iii) a bottom effect, though 20mm of bottom soil is not considered for observations but still, results show the deviation from expected trend because of hindrance from the bottom rigid surface disturbing the pattern of full flow around T-bar,

(iv) an anchorage effect, during the beginning of the upward movement of the T-bar, is observed between 10 to 20 mm from the bottom,

(v) a regular trend, same as (ii), regular trend with complete development of full flow around T-bar but $S_u$ measured is of lesser magnitude than that measured by (ii) due to remolding of soil. It is important to notice that results of (ii) and (v) are useful for sensitivity of soil measurement and finally,

(vi) a soil uplifting effect: the T-bar coming upwards near the surface of soil drags out soil due to the absence of any loading. The $S_u$ value is not equal to zero at the soil surface.

3.2 Comparison of $S_u$ (VST) vs $S_u$ (TBT)

In order to obtain compatibility between measurements made by T-bar and vane shear tests, it is interesting to study the ratio of measurements made by both tests. So, with this purpose, the peak value of each curve of vane shear test is compared with the average value of $S_u$ measured by T-bar test along the depth of blade insertion. It is very interesting to observe the average of the ratios measured by different numbers of tests in kaolin clay and dam sediment, and to compare them in order to see the applicability of the tests for different types of soils. So, the average value of ratio ($r$) was calculated as follows:

$$r = \frac{S_u \text{ (VST)}}{S_u \text{ (TBT)}}$$  

4 CONCLUSIONS

The T-bar test method is very appropriate for $S_u$ measurements of soft soils and sediments. The conditions of laboratory use of a T-bar test need to define rigorous testing and interpretation procedures. It is beneficial to compare VST and TBT with clockwise rotation for penetration and anti-clockwise for uplifting so as to deduce the average $r$ values obtained as shown in table 4 for the tests run on KC and DS soils.

Table 4. Proposed average $r$ factor values for tested soils.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>$r$ (Su peak)</th>
<th>$r$ (Su remolded)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolin clay</td>
<td>1.70</td>
<td>0.60</td>
</tr>
<tr>
<td>Dam sediment</td>
<td>2.60</td>
<td>0.85</td>
</tr>
</tbody>
</table>

REFERENCES


3) Dosso, M., (2013): The influence of several parameters on the measurements of the undrained shear strength using the T-bar test, Master report, Paris 6 University, 37p (in French).


