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An efficient tool to determine S_u of soft soils

Un outil efficace pour déterminer S_u des sols mous.

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ABSTRACT: Disturbance encountered when testing soft soils both in laboratory and in-situ conditions makes the determination of undrained shear strength, S_u, very challenging. This paper introduces a new tool called "Cylindrical Shear Tool" (CST) to measure the undrained shear strength of soft soils. Description of this tool is given and the related shear test procedure is detailed. The proposed tool offers the advantage to avoid the disturbance of soft soils prior to the related shear test. From recorded measurements, and based on considerations of the existing shear tests, a specific method of determination of S_u is proposed. Experimental programme included laboratory tests by using two sizes of the CST. The recorded results on a reconstituted Tunis soft clay were compared with those obtained from direct shear tests, conducted on the same sample, and to triaxial test.

KEYWORDS: Undrained cohesion, Cylindrical Shear Tool, shear test, soft clay, disturbance

RÉSUMÉ : Lors des essais en laboratoire et in-situ les sols mous subissent un remaniement de leur structure, ce qui rend difficile la détermination de la cohésion non drainée S_u. Le présent papier introduit un nouvel outil appelé « outil de cisaillement cylindrique » (CST, Cylindrical shear tool) qui mesure la cohésion non drainée des sols mous. La description de l'outil proposé et la procédure de l'essai de cisaillement qui lui est associé sont détaillées. Le nouvel outil offre l'avantage d'éviter le remaniement du sol qui se produit avant la phase de cisaillement durant l'insertion de l'outil associé à cet essai.

A partir des mesures effectuées, et en se basant sur les considérations d'autres essais de cisaillement existants, une méthode spécifique de détermination de S_u est proposée. Le programme expérimental a comporté des essais au laboratoire comprenant l'utilisation de deux tailles différentes de l'outil CST. Les résultats des essais effectués sur la vase molle de Tunis ont été comparés à ceux obtenus à partir de l'essai de cisaillement direct réalisé sur le même échantillon et à partir de l'essai triaxial.

MOTS-CLES: Argile molle, cohésion non drainée, essai de cisaillement, outil de cisaillement cylindrique, remaniement

1 INTRODUCTION.

Determination of the undrained cohesion, S_u, requires a particular attention due to the very low permeability, colloidal and compressible structure of very weak deposits, particularly soft clays.

Sampling of soft clays induces an alteration of their structure that consequently affects the strength parameters determined from laboratory tests. Therefore, the undrained cohesion often depends on the quality of the soil samples, (Bobei and Locks, 2013).

In this framework, researchers at the Geotechnical Engineering laboratory of the National Engineering School of Tunis attempted to improve the accuracy of undrained cohesion measurement from the vane test by proposing a limitation of the recorded torque. It consists of capturing the soil failure in the range of small strains, Bouassida and Boussetta (1999). Later on, based on this condition which is applicable for all soft soils (Bouassida, 2006), then Bouassida and Azaiez (2018), presented more details to suitably determine the S_u value.

In continuation of these efforts, seeking for a reliable S_u determination, since 2016, Bouassida and Azaiez (2020) came up with a novelty test capable of remedying limitations of the existing methods. The proposed method, from the research project, still in progress, enables a suitably estimate of the undrained cohesion of soft soils.

Main objective of the present paper is to explain this novelty method by determining S_u using the cylindrical shear tool (CST) test. Reliability of the proposed method is ascertained by recorded data from the CST test compared with measurements from the direct shear test (DST) and triaxial tests.

This paper, first, tackles the soil characterization, description of the proposed CST and instructions for its use. Detailed experimental programme comprised CST tests carried out on reconstituted Tunis Soft Clay (TSC) samples. Then, the method of determination of undrained cohesion is explained with focus on the soil-failure characterization.

Obtained results from the CST tests are compared to those recorded from direct shear tests performed on the same soil sample and from UU triaxial data conducted by Bouassida and Boussetta (1999).

2 STATEMENT OF THE PROBLEM

North and South Lakes of Tunis City are the most problematic construction sites, in terms of ground conditions, due to the presence of deposited sedimentary soil of the recent quaternary age (Kaàniche et al., 2000). Several contributions, including experimental and theoretical ones, were conducted at the soil mechanics laboratory of the National Engineering School of Tunis, to investigate the study of Tunis Soft Clay (TSC). Soil characterization, implementation of constitutive laws and improvement techniques were reported (Bouassida 1996; Bouassida and Porbaha 2004; Touiti et al, 2009: Bouassida and Klai 2012, Frikha et al, 2013, Jebali et al, 2017, etc.).

Based on this acquired background related to TSC, for the present study, it is obvious to suggest a novelty method of determination of the undrained cohesion. Hence, one can expect obtaining results and judge their reliability after comparison of CST test results with previous results suggested by other methods.

3 RECONSTITUTION OF TUNIS SOFT CLAY (TSC)

Soil reconstitution comprises the preparation of specimens and their consolidation in specific cells. Experimental investigation started with sampling a TSC block extracted at 35 m depth at J. Jaures Avenue in Tunis City. Grain size distribution indicated that dimensions of 98 % particles are lesser than 80 µm (Jebali et al., 2017).

In order to guarantee both the saturation and weak consistency of the reconstituted soil, the fraction of fine particles of dimensions lesser than 100 µm hydrated at a water content equals 1.25 to 1.5 times its liquid limit. Final step comprises fill in and smooth vibration of this slurry in a consolidation cell. This typical reconstitution procedure provides obtaining TSC sample with a uniform soil texture and well-controlled physical parameters, especially its water content (Bouassida, 1996).

The consolidation cell made up of epoxy resin material, denoted C_1, is of inner diameter D_{in}= 19 cm, and height H_t = 45 cm. Figure 1 illustrates this cell mounted to the loading frame to ensure the consolidation of reconstituted soil (Tounekti et al. 2008).

Table 1 shows the recorded parameters of reconstituted TSC. Incremental applied load to cell C_1 produced a vertical stress equals 30 kPa. Worth noticing that physical parameters of reconstituted TSC in the present study are quite similar to those proposed by Bouassida and Boussetta (1999).

Figure 1 Consolidation of Tunis Soft Clay

Especially, the plasticity index of the two tested reconstituted soft soils corresponds to a high plastic clay. Besides, due to the recorded negligible undrained friction angle, TSC is a purely cohesive soil of undrained cohesion less than 12 kPa.

4 TESTING METHOD

Figure 2 displays the Cylindrical Shear Tool (CST) having a quite similar shape of the Shelby tube sampler. The CST, as designed, provides the measurement of undrained shear strength, straightforward, in comparison to existing testing methods, especially for soft clays. Noted that, prior to the beginning of the shear phase of the CST test, no soil disturbance occurs. Contrarily to the vane test for which, prior to the shear phase (applied torque to the blade), the vane insertion produces the disturbance of the soft soil.

4.1 CST description

The design of CST considered two different sizes: a small size tool and a big size tool denoted SST and BST, respectively (Figure 2). The BST, has an outer diameter D_{out} = 63.55 mm and an inner diameter D_{in} = 60.50 mm whilst the outer diameter and inner diameter of the SST are D_{out} = 38.0 mm; D_{in}= 35.20 mm, respectively. The proposed tool is a thin hollow cylindrical tube with sharpened tip over a short distance d0 =5 mm. Such a shape facilitates the penetration of the CST into the soft soil, at a prescribed vertical displacement rate, over a distance: $d_0 \leq d \leq d_f$ (Figures 3a, 3b & 3c).

Table 1. Geotechnical parameters of reconstituted Tunis soft clay

Parameter	*Present study*	*Bouassida and Boussetta (1999)*
Total unit weight (kN/m3)	*16.98*	*16.6*
Water content (%)	*51.27*	*51*
Average water content (%)	-	*34.45*
Specific gravity	*2.77*	*2.64*
Liquid limit (%)	*55.0*	*73.0*
Plasticity index (%)	*27.35*	*47.0*
Consistency index I_c	*0.14*	*0.47*
Consolidation stress σ_c (kPa)	*30*	-
Undrained cohesion (kPa)	-	*8.0*
Undrained friction angle (°)	-	*3.0*

Figure 2 Proposed tool designed in two different sizes; SST (right side) and BST (left side)

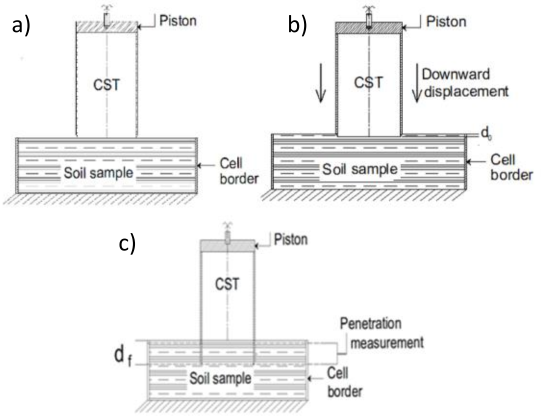

Figure 3 CST test procedure a) Positioning of the Cylindrical Shear Tool (b) Initial tool penetration (Before measurement), (c) Final tool penetration (End of measurement)

Figure 4 shows the Cylindrical Shear Tool [1]; it comprises two main parts; a hollow cylinder [2], to shear the soil, fixed to a piston [3] that constitutes the second part of the CST.

The annular ring [4] is composed of an inferior disk [6] that seals the upper side of the hollow cylinder from inside. Superior disk [7] of a diameter equals to the outer diameter of the hollow cylinder, prevents the piston sliding into to the hollow cylinder.

The piston is fixed to the hollow cylinder thanks to three headless socket screws fixed within three equal bows around the inferior disk [6], (Bouassida and Azaiez, 2020). The piston [3] transmits the soil reaction against the imposed rate of vertical displacement by means of headless socket screw fixed, [5], to the load cell recorder.

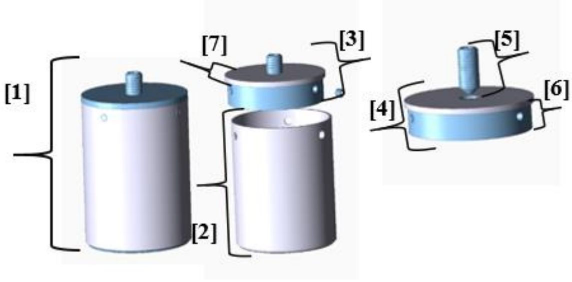

Figure 4 Components of the proposed tool

4.2 Detailed procedure of the CST test

For implementing the proposed test, the cutting of cell C_1 in three equal portions gives three soil specimens. On both sides of each portion, the proposed undrained shear test using the CST was carried out. The upper and bottom sides of the obtained portions 1, 2 and 3 are denoted 1US, 1BS, 2US, 2BS, 3US and 3BS, respectively.

On the top and bottom sides of each portion, two CST tests were performed by using the SST and one test by the BST. Figure 5 depicts the locations of those tests. Note that recorded results by the CST came from tests performed on the second and third portions of reconstituted samples.

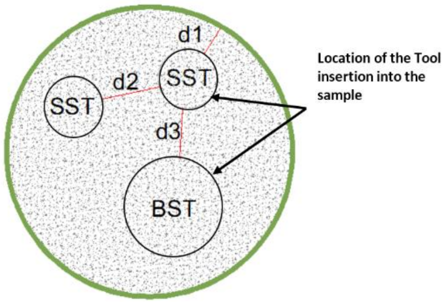

Figure 5 Locations of CST tests performed on a side of sample portion

In Figure 5, distances between performed tests are:

d1= Distance between the CST test and a portion border: 1.5 cm to 2.5 cm.

d2= Distance between two CST tests performed with the SST: 4 cm to 5.5 cm

d3= Distance between two CST tests performed with the SST and BST: 4 cm to 5 cm

Figure 6 shows the whole CST apparatus (5) and measurement-assessing transducers (3) and (4) mounted to the loading frame of the triaxial tests (2). The CST fixed in the current position of the conventional loading frame of the triaxial test, penetrates the sample at a uniform vertical displacement rate applied by the moving base platen fixed to the motor drive of the triaxial apparatus.

Figure 6 displays an s-type load cell (3), of 2 kN capacity, that records the developed force P balancing the soil resistance when the CST penetrates the sample.

Figure 6 also shows a displacement transducer “4”, VJT0271 of 25 mm travel distance, to record the displacement of the CST when pushed upward to the sample. A GDS lab software controls all data acquisition. Prior to the test, one checks, on the motor drive that the prescribed displacement rate of 1.25 mm/min satisfying the undrained shear condition. After checking the GDS lab connection, the CST test starts by the penetration of the sharpened tip of the CST into the sample, and then follows the re-initialization of all transducers reading to zero to pursue the CST test.

Intact specimens extracted from the two portions of the consolidation cell C_1 served to conduct direct shear tests (DST).

5 METHOD OF S_U DETERMINATION FROM THE CST TEST

According to the French standard, NF–P 94, from the direct shear test, soil resistance is determined in the range of a horizontal displacement less than or equal to 5 mm in absence of the peak of load-displacement curve.

Figure 6 Complete mounting of the CST and measurement accessories of the triaxial load frame

Therefore, the soil-failure shear strength requires a limitation on the horizontal displacement of the shear box. Westerberg et al. 2015 also proposed a limitation to estimate the undrained shear strength from the direct shear test by setting at a maximum distortion angle of 15 radians and adopting the maximum value of Su recorded between 10 and 15 radians.

In this study, the direct shear test served as a referential to calibrate empirical factor for determining the undrained shear strength from the field vane test, cone penetration and fall cone tests.

Further, establishing a limitation on the vane rotation, as suggested by Bouassida and Boussetta (1999), shall allow a correction method for the vane test, which applies for any type of soft soil. Indeed, the proposed correction factor, proposed earlier by Bjerrum, revealed non-applicable to determine a non- overestimated undrained cohesion of Japanese marine clays (Tanaka, 1994). Later on, Bouassida and Azaiez (2018) implemented the same approach to interpret in-situ vane test data, then, a limitation on the rotation of the vane apparatus, in a prescribed range revealed satisfactory to avoid the overestimation of undrained cohesion of river sediments.

When running the CST test, the imposed rate of vertical displacement (penetration d) is identical to the imposed rate of horizontal displacement during the direct shear test. From Figure 7, the sample distortion (shear deformation) is equal to $\frac{2\,d}{D_{int}}$.

Based on this consideration, when running the CST test, a limitation of the tool penetration should apply to measure the ultimate force P_{ult}, and then, to determine, safely, the undrained cohesion. Hence, the mobilized soil shear strength does not always correspond to the peak of stress-strain (or force-displacement) curve recorded from any shear test (Bouassida, 2006). Worth noted that limitation of the penetration, d, of the CST into the soft soil also applies for the sheared soil-CST contact area:

$$A_{sh} = \pi\,(D_{in} + D_{out})\,d \qquad (1)$$

The developed shear strength over area Ash depends on the adhesion and frictional angle of the interface existing between the CST and penetrated soil. In undrained condition, for soft soils (e.g. soft clays) those interface failure parameters reduce to the undrained cohesion, since their undrained friction angle is nearly zero. Table 1 confirms this property for Tunis soft clay.

Recorded vertical force P versus the CST penetration d of tests carried out on the second and third portions of cell C_1 results in curves with a shape identical to the example of evolution of P versus d illustrated in Figure 8 as recorded for the third portion of C_1.

From the obtained curves, the ultimate force P_{ult} to consider for estimating the undrained cohesion of tested soft soil S_u, is determined following the method of construction depicted in figures 8. P_{ult} value corresponds to the starred dot intersecting the first non-linear portion of the force-penetration curve and the asymptotic quasi-linear portion of this curve. Considering the captured value P_{ult} from P evolution to the CST penetration d, and taken account of Eq (1), the calculation of the undrained cohesion follows from Eq (2) in which d_{ult} denotes to the captured P_{ult} value on the force-penetration curve shown in Figure 8.

$$S_u = \frac{P_{ult}}{\pi(D_{in}+D_{out})\,d_{ult}} \qquad (2)$$

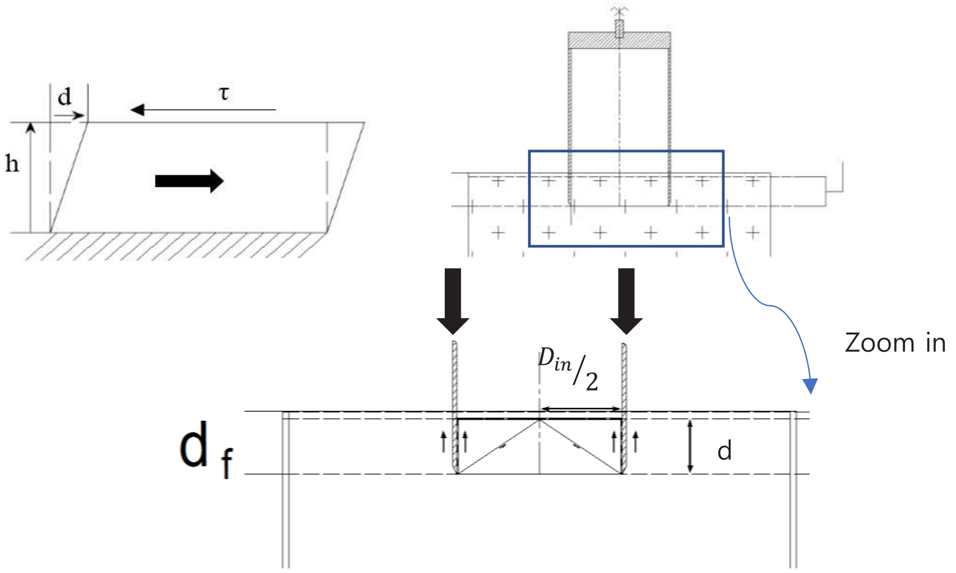

Figure 7 Similarity of shear strains during the DST and the CST

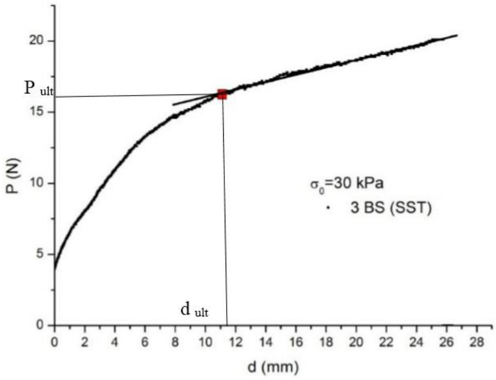

Figure 8. Variation of the strength resistance P vs the penetration d in the third portion of the consolidation cell $\sigma_c = 30\ kPa$

6 INTERPRETATION OF RESULTS

Are considered recorded results from, first, CST tests carried out in cell C_1 where the consolidation of TSC occurred under 30 kPa vertical stress; and, second, results of DST performed on extracted samples from the cell C_1. Table 2 presents the recorded ultimate vertical force P_{ult} and corresponding estimations of S_u from CST tests and results of DST all carried out on sample portions obtained from the reconstituted soft soil in cell C_1.

Assessment of the proposed method to determine the undrained cohesion of TSC from the twelve performed CST tests in the consolidation cell C_1 is processed. First, one determines the average of S_u values obtained by the CST tests performed on each side of a cell portion.

Table 2 displays those values, i.e. 9.43 kPa, 12.51 kPa, 7.91 kPa and 9.16 kPa.

Second, one consider two Su values recorded from three performed DST on samples cut from the consolidation cell C1

(Table 2). Then, using Eq. (3), follows the calculated relative error percentage between averaged Su values determined from data recorded by the CST and the DST.

$$\Delta S_u = \frac{|S_u{}^{DST} - S_u{}^{CST}|}{S_u{}^{DST}} \qquad (3)$$

One notes that the recorded values of undrained cohesion S_u are in a better agreement with those recorded for the second portion, than for the third one, of the reconstituted soft soil in consolidation cell C_1. Those S_u values were in the range 8.72 to 12.41 kPa and from 7.2 to 11.38 kPa, respectively.

In the second portion, i.e. located at the middle of cell C_1, DST results underestimate those obtained by the CST by 0.79% that is negligible for estimating the Su values.

Further, from Table 2, the determined Su values by the CST are very comparable to those determined from the direct shear test (DST). In fact, for the soil portion 2US, the ratio $\frac{S_u{}^{CST}}{S_u{}^{DST}} = 1.01$ that indicates a good agreement between the DST and CST test results.

In the third portion, i.e. located at the bottom side of consolidation cell C_1, DST results overestimate those obtained by the CST in the range 12.8% to 24.7% that is non-negligible since Su values are quite small. It corresponds to an average ratio $\frac{S_u{}^{CST}}{S_u{}^{DST}} = 0.82$. Such a relative difference between Su values is acceptable when measuring the undrained shear strength (Van Impe and Verastegui, 2007).

One can adopt an average Su value from results of all tests carried out by the CST over the entire height of cell C_1 (Table 2). Indeed, for the purpose of comparison, the height of reconstituted sample in this cell, of 45 cm, is nearly equal to the length of a Shelby tube to obtain intact-cored soil specimens.

Measurements from the proposed DST herein, summarized in Table 3, led to values of average Su equal to 9.36 kPa and 10.5 kPa in the second and third portions of consolidation cell C_1, respectively. It resulted a first average value $S_u{}^{DST} = 9.93$ kPa for the overall reconstituted soil within the consolidation cell C_1. From the latter, it follows an average value from CST tests: $S_u{}^{CST} = 9.75$ kPa that is in good agreement with the average Su value recorded from DST data.

Table 2. Recorded undrained cohesion by the CST test and DST performed on a reconstituted specimen.

Cell C_1 portion (*)	d_{ult} (mm)	P_{ult} (N)	$S_u{}^{CST}$ (kPa)	$S_u{}^{CST}$ (kPa) (Average)	$S_u{}^{DST}$ (kPa)	Relative difference (%)	$\frac{S_u{}^{CST}}{S_u{}^{DST}}$
2US BST	5.59	19	8.72				
2US SST	7.55	15	8.64	9.43	9.36	0.79	1.01
2US SST	6.36	16	10.94				
2BS BST	8.77	45	13.17				
2BS SST	8.06	23	12.41	12.51	-	-	-
2BS SST	7.63	21	11.97				
3US BST	5.99	20	8.57				
3US SST	7.1	13	7.96	7.91	10.5	24.67	0.75
3US SST	6.04	10	7.20				
3BS BST	7.16	24	8.60				
3BS SST	8.13	14	7.49	9.16	10.5	12.79	0.87
3BS SST	9.17	24	11.38				
Total average				9.75	9.9	1.81	0.98

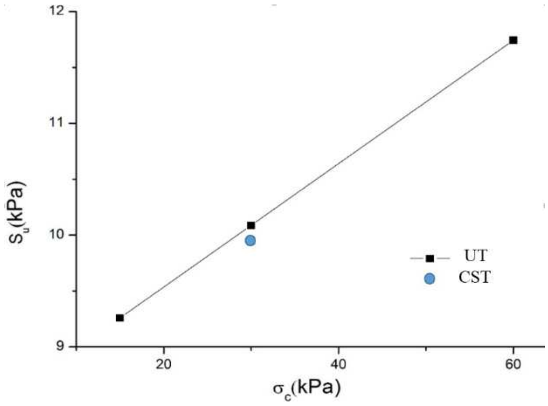

Figure 9 Comparison of obtained $S_u{}^C$ measurement with undrained triaxial test (Bouassida and Boussetta, 1999)

6.1 Comparison of CST and UU triaxial test results

Figure 9 shows undrained cohesion values from unconsolidated undrained triaxial (UT) tests, performed on initially consolidated TSC specimens at different values of consolidation stress, i.e. 10 kPa, 30 kPa and 55 kPa (Bouassida and Boussetta, 1999). This figure also displays the average undrained cohesion proposed from the CST tests run on three portions of the cell C_1 consolidated at 30 kPa. It is noted the good agreement between the undrained cohesion values of specimens consolidated at 30 kPa, i.e. with negligible relative difference is: $\Delta S_u = \frac{|10.087 - 9.75|}{10.087} = 3.34\%$.

One can argue this interesting finding by two facts. First, the reconstituted TSC samples of the present experimental program came from soil extraction at Jaures Avenue in Tunis City. Whilst, Bouassida and Boussetta (1999) investigated, TSC samples extracted from the south Lake of Tunis. Those two sites, located in nearby areas of Tunis City, belong to the same geological era and clay deposit. Second fact, is the assessment of the proposed method of determination of Su from the CST test results. It reveals that this method of determination is justified since it provides quite similar values of the undrained cohesion determined from undrained triaxial tests. Noted that the two reconstituted TSC specimens have equal water contents, i.e. 51.27 % and 51.0 % (Table 1).

7 CONCLUSIONS

The present paper dealt with the determination of the undrained cohesion of soft soils using the called “Cylindrical Shear Tool” (CST). The merit of the novelty designed CST was to avoid the soil disturbance that often occurs before the commencement of existing in-situ tests (e.g. vane shear, pressuremeter, etc). Main findings of this research-development work follow.

Conducted experimental program, first, included the reconstitution of Tunis soft clay samples in a consolidation cell. Second, followed a detailed description of the CST, designed with small and big sizes. Procedure of the shear test using the CST was introduced, then, followed by shear tests by the CST were performed on reconstituted TSC samples.

Using existing TSC data, i.e. undrained cohesion determined from direct shear tests (DST) and triaxial tests, the assessment of CST tests results was proceeded. Main finding is CST tests results could underestimate the DST results with a relative difference of 24.7%.

Measured undrained cohesion is independent from the CST diameter. The above primary findings, suggested from CST investigations, need further assessment by testing other types of soft soil.

Nonetheless, advances by the CST are in progress to determine the shear strength of other soil types.

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