New Tool for the Measurement of Soils' Shear Strength

Mounir Bouassida and Dalel Azaiez

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, S_u, 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 measurement of shear strength. From recorded measurements, and based on considerations of the existing shear tests, a specific method of determination of S_u is proposed. Recorded results by the CST on a reconstituted Tunis soft clay revealed in fair agreement with those obtained from direct shear tests and from a triaxial test. Using the CST a series of tests was also performed from which the friction angle of the interface between the CST and a compacted sand is determined. First, characterization of the chosen quarry sand comprised identification tests, Proctor tests and the direct shear test (DST). Then follows the preparation of sand samples compacted, in Proctor molds, at the optimum modified and normal Proctor water contents. Those remolded sand specimens were subject to the CST tests for which the failure shear strength is captured. Then the method of determination of the sand specimens' friction angle is detailed.

Keywords Cohesion · Testing · Disturbance · Cylindrical tool · Friction angle · Undrained cohesion

1 Introduction

The determination of soil shear strength relies on producing failure within the soil when subjected to a given loading path. Then, after the measurement of the ultimate load, follows the identification of the soil strength parameters using a specific method

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that depends on the used test procedure. Testing methods to produce a soil failure mostly comprises laboratory tests and in-situ tests.

For laboratory tests, all performed under a prescribed loading rate, one can impose the surface failure as for the direct shear test. In turn, the surface failure is unknown and sometimes non-visible as observed when conducting classical triaxial tests. Instead, for in-situ tests other failure scenarios are considered. For the cone penetration test (CPT) a localized static failure results from the penetration of the tip of cone apparatus into the soil, then the tip resistance is measured. Using well-established correlations, one can deduce the deformation and strength parameters: the Young modulus, friction angle, and the undrained cohesion from the measured tip resistance, etc. For the pressuremeter test, a lateral expansion under a monotonic applied pressure induces a shear deformation up to failure of the surrounding soil [2]. From the measured limit net pressure and pressuremeter modulus, using a specific method, one can proceed for the design of foundations.

In a different way, the vane test, performed both in laboratory and in-situ conditions, is restricted to the measurement of a unique strength parameter that is the undrained cohesion of soft soils. This set of soil investigation methods also includes the dynamic penetration tests, in particular the Standard Penetration Test (SPT) and the dynamic cone device during which a number of blow counts corresponding to a prescribed penetration depth, permits to derive specific strength parameters based on well-established correlations. In case of sands, one can determine the friction angle using the well-know Terzaghi and Peck correlation, Das [8]. In a quite different manner, from the dynamic cone penetration, from the recorded soil resistance, an estimate of the admissible bearing capacity of a shallow foundation is obtained [7].

From the above flashback related to soil testing methods, e.g. tools, for determining in particular shear strength characteristics, there is no limitation, in terms of test procedure, to produce the soil failure, and also to choose the suitable method for determining strength parameters. However, one can outline an important detail that is soil disturbance that can happen into the soil, or not, for the performed testing procedure. Based on this, one can proceed for a classification concerning the preparation for the shear strength measurement. In this regard, one can notice for the vane test that, prior to the commencement of the loading (applied torque), the vane penetrates into the specimen (in laboratory) or the in-situ ground, then, there is a disturbance which may affect the test results [1]. As for the pressuremeter test, the boring of the soil significantly disturbes the vertical edge of the created hole where the measurements cell is mounted to start the lateral expansion. In addition, after discussing the estimation of the undrained cohesion of soft soils, [9] reported the overestimation the S_u value from the recorded limit net pressure during the pressumeter test.

In a different way, concerning the static cone penetration test (CPT) and the standard penetration test (SPT), the measurement of soil shear strength occurs at the bottom of a created hole, and precisely, after an initial penetration of the apparatus where no measurement is taken. As such, one can endorse the fact that soil disturbance will not affect the measurement of soil resistance beyond the initial penetration. Further, especially for the CPT and SPT, note that from the measured resistance, there is a need to use recommended correlations that essentially depend on the soil type to derive the foreseen strength soil parameters. Therefore, results from the existing is-situ tests do not provide a direct measurement of the basic failure parameters i.e. cohesion and friction angle. Figure 1 schematizes the differences between four in-situ tests, as described in the above, to show where the soil disturbance affects, or rather not, the measurement of soil failure parameters.

Worth mentioning to date there is a lack for determining a reliable undrained cohesion for soft soils. In fact, dependent less of the existing testing tool the disturbance of soft soil in inevitable. Hence, there is a real need to seek for a tool avoiding the soft soil disturbance to assure a reliable S_u determination.

The present work, first, suggests the new Cylindrical Shear Tool for the measurement of soil shear strength recently introduced and patented [4]. This tool enables a direct determination of the undrained cohesion of soft soils without the occurrence of disturbance. Second, this paper presents, a step further, to detail how the use of the cylindrical shear tool (CST), enables the determination of the friction angle of cohesion less soils. The main outcome of the CST relies on the direct and reliable determination of cohesion and/or friction angle without being affected by the soil disturbance.

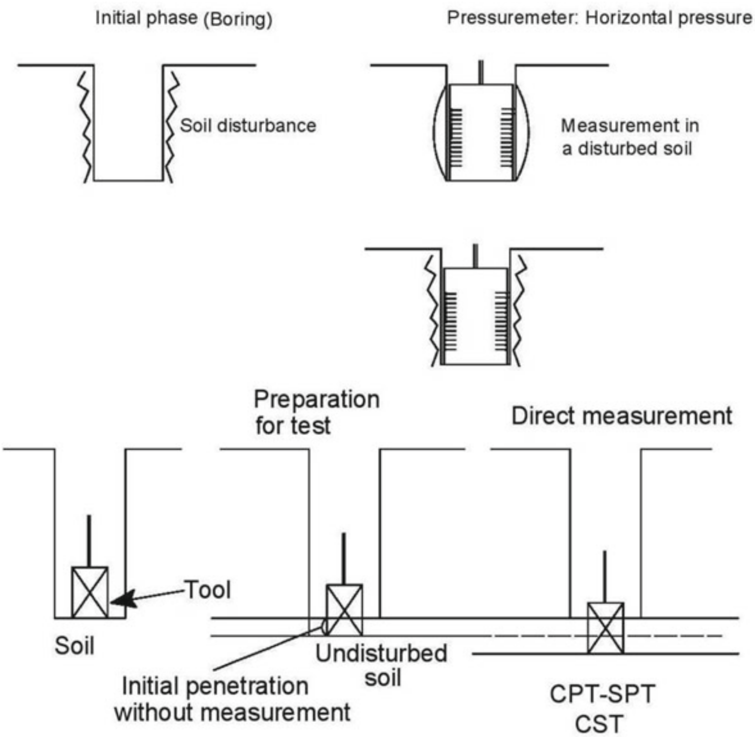

Fig. 1 Schematized preparation for in-situ tests illustrating the occurrence of soil disturbance

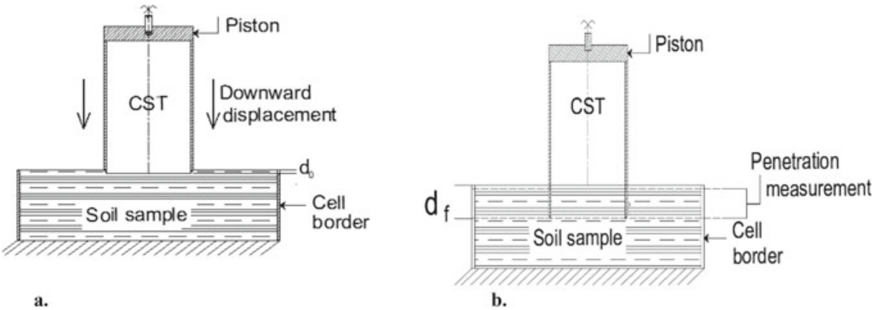

Fig. 2 **a.** Initial penetration of the cylindrical tool into the test soil prior to the measurement; **b.** Penetration of the cylindrical tool into the test soil during the measurement of the soil resistance

For each soil type's this paper details the method of determination of its shear strength parameter from the recorded load displacement curves. The validation of the CST test results is discussed after comparison with results obtained by the current testing methods.

2 The Cylindrical Shear Tool (CST)

2.1 Tool Design

The proposed tool is a thin hollow cylindrical tube with a sharpened tip over a short distance $d_0 = 5$ mm. Such a shape facilitates the penetration of the CST into the soft soil, at a prescribed vertical displacement rate, over the distance d_0 (Fig. 2a and b).

The recently published CST test procedure enables the measurement of the soil resistance developed along the circumferential shaft of the penetrated hollow cylinder over the recorded penetration d in the range d_0 to d_f. Therefore, the CST enables a direct measurement of the soil resistance over the imposed soil-tool interface.

Bouassida and Azaiez [3] provided a detailed presentation of the components of the CST for which two sizes, small and big, served for the determination, as a first investigation, of the undrained cohesion of a remolded Tunisian soft clay.

Figure 3 illustrates the two sizes of the manufactured CST for the determination of the soil shear strength parameters.

2.2 Testing Procedure

As experienced during the first investigation [3], the CST test and measurement-assessing transducers are mounted to the loading frame of the triaxial apparatus. The

Fig. 3 Proposed cylindrical shear tool designed in two different sizes

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.

An s-type load cell, of 2 kN capacity, records the induced vertical force P balancing the soil resistance when the CST penetrates the soil sample.

Besides, using a displacement transducer "4", VJT0271 of 25 mm travel distance, one records the displacement of the CST when pushed upward to the sample.

Prior to the commencement of the test, one checks, on the motor drive the prescribed displacement rate satisfying either the undrained shear condition or the drained one.

A GDS lab software controls all data acquisition. After checking the GDS lab connection, the first stage of the CST test starts by the penetration of the sharpened tip of the CST into the sample. Then, the re-initialization of all transducers reading to zero to start the second phase corresponding to the CST test that is the shearing of the tested sample. Such a procedure appeals to derive along the soil-tool interface, either the cohesion, in case of soft soils, or the frictional angle governing the contact between the CST and a granular soil.

2.3 Determination of Soil Shear Strength Parameters

Main experimental output from the CST test is the recorded load-penetration curve. After the first investigation, for determining the undrained cohesion of soft soils, Bouassida and Azaiez [3] reasoning's considered the similarity between the direct shear test (DST), and the CST test by concluding the need to mark a limitation of the CST penetration to capture the ultimate vertical force P_{ult}.

As such, one can determine, comprehensively, the soil shear strength parameters. In fact, earlier, Bouassida, [6] explained that the mobilized soil shear strength does not always correspond to the peak of stress–strain (or force–displacement) curve recorded from any shear test. Worth noted that the limitation of the penetration, d, of the CST into the soft soil also applies for the soil-CST contact area.

3 Determination of Soft Soils' Undrained Cohesion: An Update

Figure 4 shows the variation of the axial force versus the CST penetration as recorded during several tests carried out on reconstituted Tunis soft clay samples.

For each load-penetration curve, the starred point corresponds to the value of the ultimate load determined after the method proposed by Bouassida and Azaiez, [3]. Using the recorded ultimate load, P_{ult}, and the corresponding penetration d_{ult}, illustrated by Fig. 4, one determines the undrained cohesion, S_u, of the tested samples from Eq. (1)

$$S_u = \frac{P_{ult}}{\pi(D_{int} + D_{out})d_{ult}} \tag{1}$$

D_{in} and D_{out} denote the inner diameter and the outer diameter of the CST.

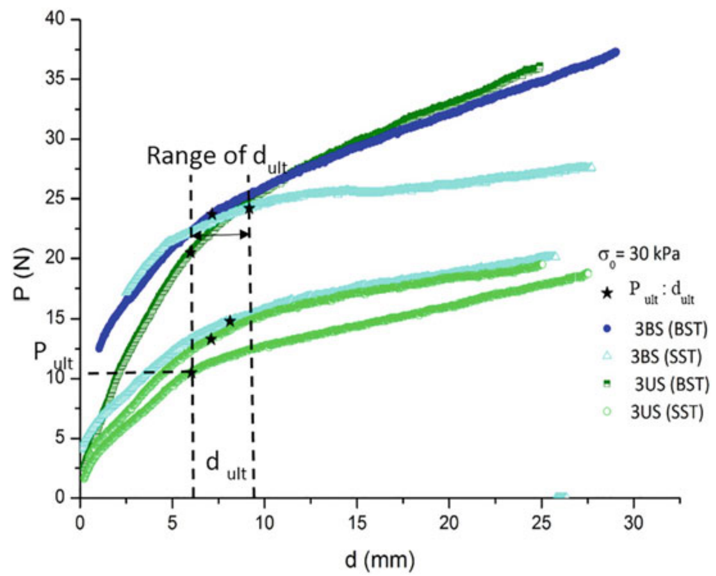

Fig. 4 Variation of the axial force versus the CST penetration in reconstituted Tunis soft clay samples under 30 kPa consolidation stress

Assessment of obtained S_u values from the CST tests showed a fair agreement with values determined for the direct shear test (DST) and a classical triaxial test [3].

4 Determination of Cohesion Less Soils' Friction Angle: First Investigation

The experimental program comprised two steps. First step considered the characterization of a selected quarry sand, including a grain size distribution, Proctor tests and the direct shear test. Second step focused on performing shear tests using the recently patented CST for the determination of the friction angle, by assuming zero cohesion for the tested sand.

4.1 Characterization of the Granular Soil

Bulk sample retrieved from a fill sand, of current use in concrete production, was subject to a sieve analysis with a mesh opening less or equal to 2 mm. Dry sieve analysis was performed after preparing one kilogram of the selected sand. Figure 5 shows, after the particles size distribution, that dimensions corresponding to 60% finer (D_{60}), 30% finer (D_{30}) and 10% finer (D_{10}) approximately take the values 0.55 mm, 0.3 mm and 0.15 mm, respectively. Those data allowed obtaining the coefficient of uniformity: $C_u = \frac{D_{60}}{D_{10}} = \frac{0.55}{0.15} = 3.67$ and the coefficient of gradation $C_c = \frac{D_{30}^2}{D_{10} D_{60}} = \frac{0.3^2}{0.15 \times 0.55} = 1.09$. After the USCS, the tested sand is classified well graded sand.

The characterization of the tested sand using the pycnometer test, led to the specific gravity value in the range: $2.608 < G_s < 2.615$; $G_s = 2.643$.

From the direct shear test carried out on a specimen of the fill sand, the shear strength is characterized by a friction angle $\varphi = 28.9°$ and negligible cohesion. Those characteristics are typical of a loose sand.

Further, after the preparation of compacted samples of the tested sand in standard Proctor molds the modified and normal Proctor procedures were carried out. Figure 6 shows the two Proctor curves as recorded from the modified Proctor and normal Proctor tests. The recorded modified Proctor parameters are: optimum water content $\omega_{op} = 8.64\%$ and a maximum dry unit weight: $\gamma_d(\text{max}) = 18.47\text{kN/m}^3$. Whilst, from the normal Proctor test, the maximum dry unit weight is $\gamma_d(max) = 17.99\text{kN/m}^3$ and the corresponding optimum water content is:. $\omega_{op} = 10.38\%$. Table 1 summarizes the recorded data from the performed Proctor tests and the calculated void ratios using the identification test results. From those data, the influence of an intense energy of compaction leads to a decrease in the void ratio and an increased maximum dry density.

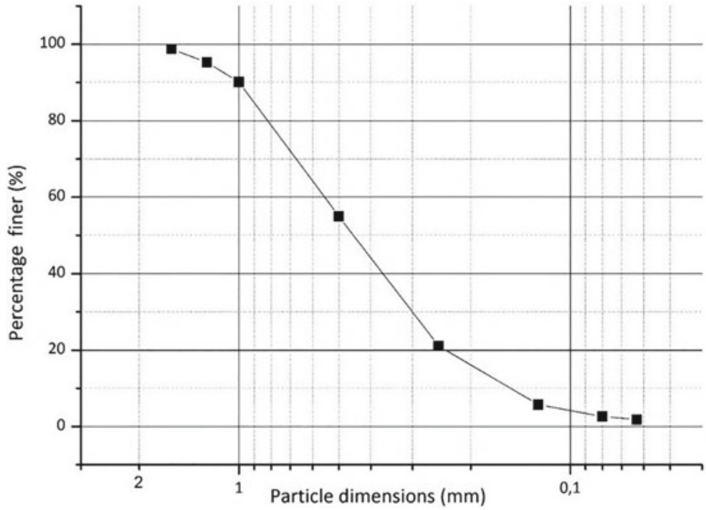

Fig. 5 Grain size distribution of tested sand

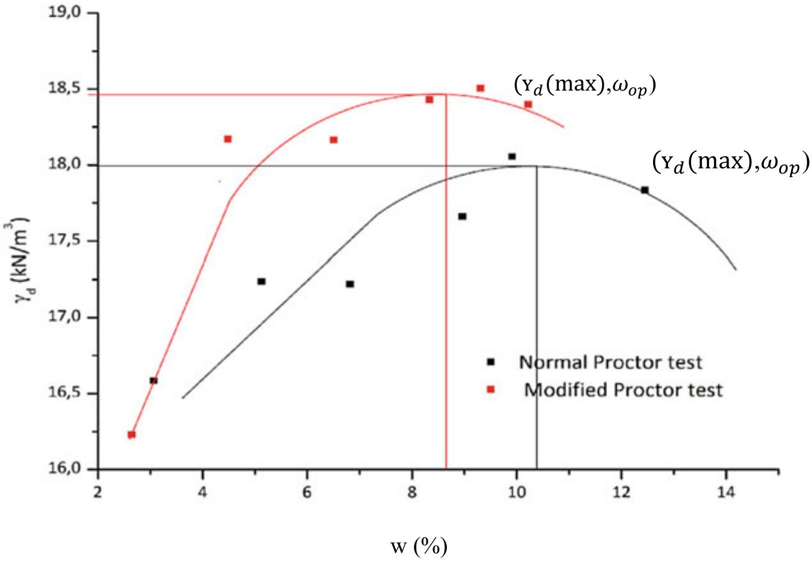

Fig. 6 Proctor test curves of the tested compacted sand

Table 1 Proctor tests results of the compacted sand

Parameters	Modified Proctor test	Normal Proctor test
Optimum water content (%)	8.64	10.38
Max γ_d (kN/m^3)	18.47	17.99
Calculated void ratio	0.552	0.622

4.2 Determination of the Friction Angle of Cohesion Less Soil from the DST and CST Results

Preparation of the sand samples to be subject to the DST and CST test consisted of the compaction of sand specimens in the CBR mold to assure controlled parameters corresponding to the referenced normal Proctor and modified Proctor compactions at related optimum water contents. Opposite extremities sides of the CBR mold specimens served for performing the direct shear tests on the compacted sand specimens.

Those specimens were, then, subject to three CST tests for which the characterization of shear strength parameters were obtained. Then, the method of determination of the friction angles of sand specimens is detailed.

Figure 7 presents the intrinsic curves from recorded results of the DST performed on compacted sand specimens for the normal and the modified Proctor tests.

Table 3 summarizes the obtained shear strength showing a substantial increase of the compacted soil specimen's failure characteristics compared to the friction angle of the dry loose sand (Table 2). The sand compaction significantly enhanced the friction angle, with respect to the performed compaction energy. In addition, the compaction also induced a non- negligible cohesion.

Figure 8 shows the variation of the axial force P versus the CST penetration into the tested compacted sand sample. Noted that during the CST penetration there are fluctuations of the recorded values by the force sensor as illustrated by the dotted band (cloud points). Equation (2) predicts the average of recorded force P (in Newton), during the second CST test performed on the modified Proctor compacted sand sample, as a function of the CST penetration d (in mm), with a linear regression coefficient $R^2 = 0.76$.

$$P = 2.43387 d_{ult} \tag{2}$$

By assuming the tested sand as a cohesionless material, the determination of the friction angle resulting from the CST penetration is owed to the developed shear strength along the interface soil-CST. The mobilized shear strength at depth "z" is given by Eq. (3):

$$\tau_f = \sigma_h \tan \delta_f = K_P\,(\gamma\, z) \tan \delta_f \tag{3}$$

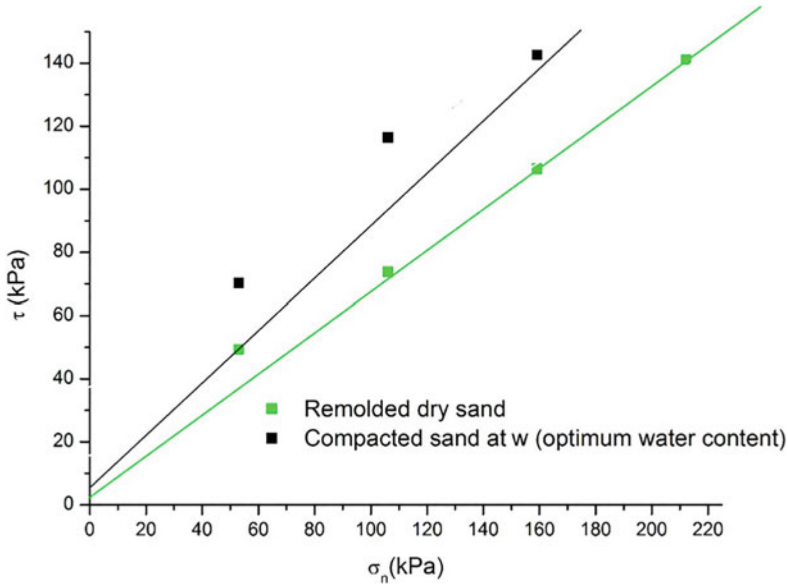

Fig. 7 Intrinsic curves from direct shear tests on the compacted dry sand and specimens at optimum Proctor water content

Table 2 Result of the direct shear test carried out on quarry sand

σ_h (kPa)	τ (kPa)	Horizontal displacement (mm)	Friction angle φ
233	127.2	5.03	28.6°

Table 3 Results of direct shear tests carried out on compacted sand specimens

	C (kPa)	φ (°)
Compacted sand	5.6	39.8
Remolded dry sand	2.6	33.0

σ_h denotes the horizontal stress applied to the CST shaft area.

K_P denotes the passive pressure coefficient which essentially depends of the friction angle of the tested sand (and the roughness of the CST-soil interface).

δ_f denotes the friction angle of the interface between the CST shaft and the tested sand.

Over the increment of the CST penetration dz: $d_0 < dz < d_f$, the vertical force balances the mobilized shear strength, corresponding to the soil failure, over the elementary area, dA_{sh}; of the CST shaft given by Eq. (4)

$$dA_{sh} = \pi\,(D_{int} + D_{out})\mathrm{dz} \quad (4)$$

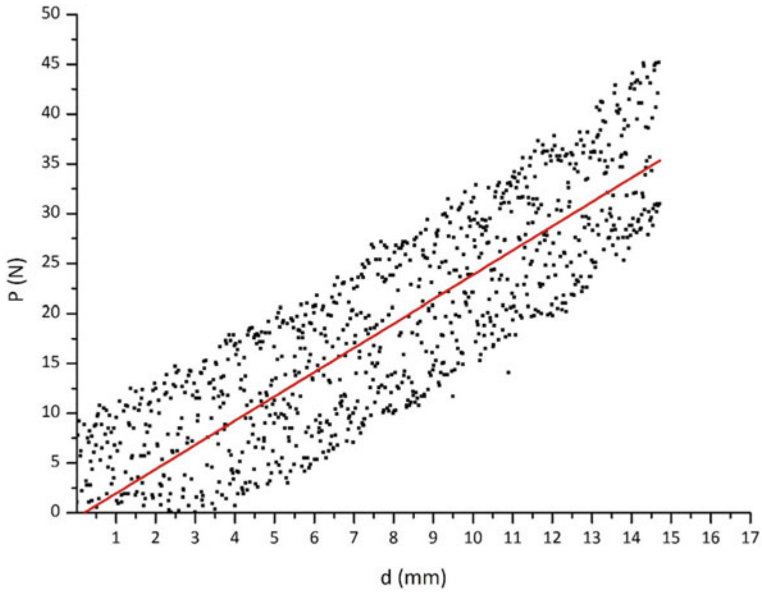

Fig. 8 Recorded axial force P versus the penetration of the CST into the compacted sand sample at the optimum modified Proctor

Using Eqs. (3) and (4), the integration of the shear strength over the total shaft area of the CST leads to the resultant ultimate axial force given by Eq. (5)

$$P_{ult} = \int_{d0}^{d_f} K_P(\gamma z) \tan \delta_f \pi \, (D_{int} + D_{out}) dz \tag{5}$$

Integrating Eq. (5), one obtains the ultimate vertical force expressed by Eq. (6)

$$P_{ult} = \frac{1}{2} \gamma (d_f^2 - d_0^2) K_P \tan \delta_f \pi \, (D_{int} + D_{ext}) \tag{6}$$

As a first basic assumption, in this work, the passive pressure coefficient is given by the well-known formula of Rankine's theory, i.e.

$$K_P = (1 + \sin \varphi)/(1 - \sin \varphi) \tag{7}$$

The effective measurement of the axial load starts after the initial penetration d_0, and the value of the ultimate axial force, P_{ult}, corresponds to a given value d_{ult} in the range: $d_0 < d_{ult} < d_f$; hence, the friction angle of the interface between the CST and the cohesion less soil is determined from Eq. (8):

$$\tan\delta_f = \frac{2P_{ult}}{\gamma d_{ult}^2 K_P \pi \left(D_{int} + D_{ext}\right)} \quad (8)$$

The friction angle of the CST-soil interface, δ_f, is proportional to the one of the tested sand, φ as:

$$\delta_f = \alpha\varphi \quad (9)$$

From the literature, in case of a positive frictional soil resistance, as for driven piles, it is common, that coefficient "α" introduced by Eq. (9) is the range:

$$0.5 \leq \alpha \leq 0.67 \quad (10)$$

Solution of Eq. (8), in terms of the friction angle of the assumed cohesion less soil, φ, cannot be obtained by performing direct resolution methods. There is a need to perform an iterative procedure for solving such an implicit equation. Plausible solutions should be targeted in the interval φ = 25−40°. This investigation is in progress to deliver the suitable determination of the friction angle of purely frictional material from the result obtained by the CST.

5 Conclusions

This paper presented the cylindrical shear tool for testing soils to determine shear strength characteristics. Main benefit of the tool is to avoid the soil disturbance prior to the measurement of shear strength resistance. First investigation considered the determination of the undrained cohesion of purely cohesive soils for which a specific method of determination has been introduced. Thanks to existing direct shear test and a triaxial test results the estimated cohesion using the CST reveals satisfactory [5]. However, more investigation are yet needed for the validation of the proposed method of S_u determination.

Second investigation focused the determination of the friction angle of assumed purely frictional sand. After characterization of a chosen quarry sand including Proctor tests and direct shear test, the influence of compaction has been evidenced by comparing the cohesion and friction angle recorded for compacted sand specimens using the normal and modified Proctor procedures.

After carried out shear tests using the CST, the method of determination of the friction angle of tested sand specimens (assumed of negligible cohesion) is formulated. This investigation is yet in progress to propose a suitable determination of the friction angle of cohesion less soils.

It is also viewed that performing the CST test makes possible the determination of the overall shear resistance of cohesive frictional soils. This third possibility applies for the compacted sand specimens at two different compaction energies.

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Since 2019, the launch of the You Tube channel « Mounir Bouassida" gained lot of interest from than 1430 subscribers. Fifty nine uploaded videos, in English and French, to this channel cover themes focusing on soil mechanics, modelling and the study of the behavior of geotechnical engineering structures.