

The LCPC triaxial press for hollow cylindrical specimens adapted to studying natural soils

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ABSTRACT

The triaxial device for hollow cylindrical specimens, developed some fifty years ago, has come to be considered as an outstanding tool for studying the behavior of soils located around geotechnical structures or subjected to alternating loadings. This set-up enabled a technological leap that would never have been possible with the classical triaxial tests on solid cylinders. An analysis of torsion tests on hollow cylindrical specimens has led to devising more complete rheological models that serve to incorporate the stress rotation phenomenon. The evolution in equipment will be presented from the original design of the LBTP (Construction and Public Works Laboratory) press all the way to the LCPC triaxial press for hollow specimens. The procedures and methodology developed at LCPC to conduct this type of test will also be discussed in detail. The article concludes by offering the initial results obtained on natural soils.

INTRODUCTION

The reorientations of principal stress directions with respect to their natural state, under the effect of an external loading, characterize the three-dimensional phenomenon called stress rotation. This phenomenon is often encountered and common to all soil and rock masses whose natural state has been disturbed. The new orientations are characterized in particular by the angle between the major principal stress and the vertical axis of the orthonormal geostatic coordinate system. Several illustrations of this phenomenon are shown in [Figure 1](#).

Many experimental research efforts have been undertaken to characterize this principal stress rotation inside soil or rock masses. Such research has focused on the influence of stress orientation on changes in the elastic domain boundary and in the formulation of both plasticity and failure criteria.

Various specimen geometries may be used to examine this influence: the segment (specimen submitted to a plane strain state), the cube (six-face triaxial press), and the hollow cylinder. Theoretically speaking, the "real" triaxial device (cubic specimen) is the only one capable of independently imposing the three principal stresses and thus of exploring the entire principal stress space. These principal stress paths however lie in non-rotational kinematics. Other so-called rotational tests have also been practiced: direct shear test of the Casagrande box variety, torsional shear tests on cylindrical or ring specimens, simple shear tests of the NGI

[1] and University of Cambridge [2] types, and lastly directional shear tests as conceived by Arthur *et al.* [3]. These setups often contain many imperfections and limitations, including:

- an imposed plane strain condition, yielding a poorly-defined stress state;
- lack of attention paid to stress rotation;
- impossibility of generating large strains;
- stress and strain uniformity problems due to specimen geometry [4]; and
- adverse boundary condition effects, magnified by the often-reduced specimen size.

Only a very few research projects have actually compared results from the stress rotation study on cubic specimens with those obtained on hollow cylindrical specimens and, moreover have actually examined their validation on foundation tests [5]. These comparative studies have shown that the torsion test on hollow cylindrical specimens was best adapted to studying stress rotation, since even though this test does not completely solve all boundary condition problems it still enables avoiding the majority and attenuating the effects of those present.

PRINCIPLE BEHIND THE HOLLOW CYLINDER TEST

This testing principle consists of introducing a torque M_t to a hollow cylindrical specimen placed under triaxial conditions by application of a vertical force F , internal pressure p_i and external pressure p_e (see Fig. 2). The principal axes then rotate from their initial state and the intermediate principal stress position varies with respect to the so-called major and minor principal stress positions. The implementation of certain stress paths or specific strain paths allows analyzing the influence of principal axis rotation.

As regards the classical triaxial shear test on a solid cylindrical specimen, the test on a hollow cylinder is characterized by the parameter b , defined by Habib [6] as:

$$b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3} \quad (1)$$

where σ_1 , σ_2 and σ_3 are respectively, according to soil mechanics convention, the major, intermediate and minor principal stresses.

During a test conducted on a hollow cylindrical specimen, rotation is measured by means of angle α , derived from construction of the pole of Mohr's circle:

$$\alpha = \frac{1}{2} \cdot \arctan\left(\frac{2\tau_{\theta z}}{\sigma_z - \sigma_{\theta}}\right) \text{ if } p_i = p_e \quad (2)$$

This measurement proves impossible within a solid or unconfined hollow cylinder. Various combinations of normal stresses σ_r , σ_{θ} , σ_z and tangential stress $\tau_{\theta z}$ must now be imposed upon the specimen in order to obtain results for different values of α . In order to distinguish the stress rotation from the principal intermediate stress, it becomes necessary to apply a pressure p_i inside the cylinder, which differs from the pressure applied outside p_e .

When p_i equals p_e , coefficient b is correlated with the stress rotation angle α via a sinusoidal function. The domain of investigation for the apparatus thus takes on the appearance shown in Figure 3. When this condition is not met, the entire space may be described, yet the rolling strain caused by some loadings creates a non-homogenous strain diagram. The radial stress σ_r is actually no longer uniform within the thickness of the specimen wall; this situation corresponds with the fourths of cones depicted in Figure 3.

With the development of measurement and servo-control techniques, it has become possible to run tests based on stresses expressed in cylindrical coordinates with respect to the specimen, then in principal stresses [5,7] or within the Lambe stress space with the variables s , t and b [8], and lastly within the Cambridge stress space (octahedral stresses) with variables p , q and α [9-11] (see Table 1).

Table 1: Stress expressions (with R_e and R_i , as defined in Fig. 2)

| | |
|-------------------------------------|---|
| $\sigma_r, \sigma_\theta, \sigma_z$ | $\sigma_z = \frac{F + \pi \cdot (R_e^2 p_e - R_i^2 p_i)}{\pi \cdot (R_e^2 - R_i^2)}, \sigma_r = \frac{p_e R_e + p_i R_i}{R_e + R_i}, \sigma_\theta = \frac{p_e R_e - p_i R_i}{R_e - R_i}, \tau_{\alpha} = \frac{3 \cdot Mt}{2 \cdot \pi \cdot (R_e^3 - R_i^3)}$ |
| $\sigma_1, \sigma_2, \sigma_3$ | $\sigma_1 = \frac{\sigma_z + \sigma_\theta}{2} + \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \tau_{\alpha}^2}, \sigma_2 = \sigma_r, \sigma_3 = \frac{\sigma_z + \sigma_\theta}{2} - \sqrt{\left(\frac{\sigma_z - \sigma_\theta}{2}\right)^2 + \tau_{\alpha}^2}$ |
| s, t, b or μ | $s = \frac{\sigma_1 + \sigma_3}{2}, t = \frac{\sigma_1 - \sigma_3}{2}, b = \frac{\sigma_2 - \sigma_3}{\sigma_1 - \sigma_3}, \mu = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$ |
| p, q, α | $p = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}, q = \sqrt{\frac{1}{2} \cdot [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]}, \alpha = \frac{1}{2} \cdot \arctan\left(\frac{2\tau_{\alpha}}{\sigma_z - \sigma_\theta}\right)$ |

As an anecdote, the triaxial test devices for hollow cylindrical specimens have been used to study the expansion of a cylindrical cavity, in order to validate the slenderness value of the pressuremeter probe required to comply with the theory of infinite-length cavity expansion. The test configurations however were indeed different: the specimens used were thick tubes and the loadings did not include torsion.

STATUS OF INTERNATIONAL LEVEL RESEARCH

According to Saada and Townsend [12], it was in 1936 when Cooling and Smith performed the first tests on a hollow cylinder to estimate the pure shear strength of cohesive soils. In their protocol, these authors submitted their specimens to torsion without any lateral confinement. Habib [13] was the first researcher to emphasize the importance of both stress rotation and the variation in intermediate principal stress by means of torsion tests on hollow cylinders. These tests were carried out at the LBTP Construction and Public Works Laboratory, subsequent to a question raised over the influence of intermediate principal stresses during a session of the French Soil Mechanics Committee (CFMS) by Florentin on April 24, 1951 [6]. The tests were executed on specimens of fine river sand with a flat particle size distribution molded into a coil shape (Fig. 4). The radial pressure was the atmospheric pressure and only the vertical force and torque were imposed in parallel in order to control parameter b (Equation 1). The operating protocol based on a manual application and control of forces, so as to conduct tests with a constant b value, proved difficult to implement.

Habib concluded that the angle of friction φ measured with Casagrande's box equaling 36 degrees actually reached 43 degrees for a median intermediate principal stress. He went on to note: "In any event, even if the torsion test were to yield extremely surprising results and potentially raise concerns, the existence of a maximum shear strength appears to be a physically undeniable phenomenon." (Fig. 5). A second series of tests on Fontainebleau sand was published in 1953 in the Annals of the Technical Institute of Building and Public Works (ITBTP) at the time of P. Habib's thesis presentation during a CFMS session.

This research and experimental campaign led by Kjellman [14] generated considerable international reaction and served as the source for many studies on the topic of stress-invariant variation during stress rotation [15].

It was not before the 1960's however that Broms and Casbarian [7] and Saada and Baah [16] would make use of the first confined hollow cylinders for the purpose of studying the effects of principal stress rotation on the shear strength of a reworked clay.

Subsequently, many studies were conducted in order to:

- determine the optimal dimensions of specimens, in order to generate as uniform a distribution as possible of both stresses and strains over the course of shearing [12,17];
- evaluate the impact of the pressure ratio on strain homogeneity [18];
- examine the anisotropy of soils and its influence on their torsional behavior [19-22]; and
- characterize the tensile strength of clays [23].

The initiation of a new wave of research on stress rotation dates back to 1983, with the work of both Saada at the Case Institute of Technology [24-27] and Symes at London's Imperial College [28]. The development of a hollow cylinder for specimens 25.4 cm in diameter within the framework of Symes' thesis program provided a crucial step in advancing the state of testing instrumentation. Afterwards, Hight *et al.* [18] performed a series of monotonic tests in both primary and cyclic loading with the rotation of principal axes on Ham River sand, along with tests for studying liquefaction problems caused by earthquakes.

More recently, Hicher assessed the influence of stress rotation and intermediate stress on shear strength, under undrained conditions, of normally-consolidated EPK clay specimens subjected to anisotropic loadings (of type K_0) as well as to monotonic and cyclic tests [29,30].

In Japan, Ishihara *et al.* [31,32] and Towhata and Ishihara [33,34] conducted cyclic tests on Toyoura sand under both drained and undrained conditions along various stress paths. The objective had been to study the liquefaction of sand exposed to an earthquake-type loading. In the U.K., research performed at the Imperial College within the scope of a number of theses has led to developing a smaller set-up adapted to natural soils and to measuring small strains [8,35,36]. In France, Karchafi [37] conducted drained torsion tests on hollow Hostun sand cylinders to assess the role of initial anisotropy in sand behavior. Other studies, relative to sand liquefaction concerns when subjected to rotational loadings, have also been completed [38].

THE LCPC PRESS FOR HOLLOW CYLINDRICAL SPECIMENS

During the 1980's, LCPC also focused on this type of promising test. Based on a feasibility study, construction of the triaxial cell for hollow cylindrical specimens by CECF Prototype Design and Construction Center in Angers began in 1984; the cell was then used as of 1987 with a 10-ton Wyckeham Farrance press. Khemissa's thesis work [39] provided an assessment of the techniques existing in other research centers and validated the equipment by a testing program on Guiche clay. Due to problems running the particular press, it was decided to build a press specially adapted to meet this set of specifications. The test acquisition and control software (servo-controlled PC) was jointly produced with the calibration benches for sensors specifically designed for this apparatus (i.e. radial displacement sensor, torque sensor). The triaxial press for hollow cylindrical specimens (French acronym: PTCC) with its cell were delivered to LCPC in 1997. Since the end of 1999, the press has been operational and the only difficulties encountered during tests conducted in 2000 were related to the software

applications. In 2001, the possibility of introducing both an internal and external pressure was added to the existing features.

n Device description

This test set-up consists, just like for classical triaxial cells, of a transparent Plexiglas enclosure containing a fluid, with the enclosure's metal cover being fitted with a vertical loading piston. The fluid pressurized by the pressure generator serves to apply radial stress $\sigma_r = p_e = p_i$. The piston, via the press, produces both axial stress $\sigma_a = F/S$ and, once set into rotation by a gear motor covering the cell, shear stress $\tau \propto f(M_t)$.

The instrumentation is composed of two pressure sensors, nine displacement sensors, an angle sensor, and a force and torque sensor. An electrical cabinet that limits disturbances of electromagnetic origin contains the various conditioning racks for the 14 sensors and control racks for the pressure and volume generators in addition to the press. The vertical loading is obtained by a heavy duty triaxial load frame. Servo-control of the four system axes (F , M_t and p_e, p_i) is introduced thanks to the Labview acquisition and control software, developed by National Instruments (digital servo-control).

To ensure that these operations take place with complete safety in the event of a deficiency in the overall network, a local network has been set up to function independently, or even to be disconnected from the main network altogether (**Fig. 6**). The user parameter ranges for this apparatus are: 0-1.5 MPa for the inside pressure, 0-100 kN for the vertical force, and 0-36 m.daN for the torsional torque.

n Test cell

The cell has been designed on the basis of the geometry selected for the specimen. Specimen thickness (1.5 cm), which is relatively small compared to specimen height, was chosen in order to yield a uniform radial stress distribution. Specimen dimensions also result from a compromise between competing requirements:

- producing high enough values for both the internal and external diameter ratio D_i/D_e and the height H , to both obtain a relatively uniform stress field and decrease the influence of hoop stresses;
- selecting dimensions that enable performing cutouts in an intact block of clay without encountering any serious difficulties; and
- ensuring the feasibility of onsite sampling (depending on the size of the core drill from Laval University; see below).

Figure 7 shows the schematic diagram along with a view of the test cell. The numbers found in the text refer to this figure. The cell is composed of a transparent enclosure made of polyacrylic containing a lower base (1), a cylinder (3) and a cover (4). The soil specimen is placed between the lower base and an upper base (2). The cell cover has been fitted with the torsional force application system (19,20).

The axial force and torque measurement sensor (13) is positioned inside the cell at the end of the piston. The link between piston and upper base ensures that the shear stresses and axial strains remain uniform over a specimen cross-section.

The enclosure (3) has been designed for a maximum pressure of 1.5 MPa and is reinforced by metal strapping so as to lessen deformability (**Fig. 7b**). The enclosure diameter has been determined for ease of specimen assembly and to accommodate ancillary systems, such as diameter measurement devices.

n Loading frame

On the whole, the types of architecture adopted for hollow cylinders can be classified into four types (**Fig. 8**). By examining **Table 2**, it is apparent that no one single architecture is predominant. Type 1, which is more classical and stems from the conventional triaxial architecture, was used by Saada [16], Lade [17] and LCPC; it is composed, like the classical triaxial presses, of a column press and a transparent cell, or enclosure, containing a fluid and equipped with a piston crossing the upper cover. The rotation or torque is transmitted by this same piston over the upper part (**Fig. 8**, case 1). Type 2 only exists in France and was created by the ENTPE Engineering facility [38,40]. Type 3, developed in England by Hight [18], was imported into Japan by an Imperial College alumnus.

A more modern design, based on Bishop and Wesley's cell concept, is now being favored and has already been implemented by the GDS company and the University College of Dublin (Type 4 on **Fig. 8**) [42]. This set-up is more manageable to use and simple to integrate. Despite its lighter structure, this equipment is not necessarily more flexible (from a mechanical standpoint). In reality, all the stiffness lies in the cell, which absorbs torque via the enclosure and vertical force via a tensioning of the columns.

Table 2: Summary table of the various types of devices

| Organization | Type | Author | Year | Specimen size (mm) | | |
|--|---------------------|------------------------------|------|--------------------|----------------|----------------|
| | | | | H | D _e | D _i |
| CEBTP, Paris | 1 | Habib [13] | 1952 | 87 | 35 | - |
| Royal College of Science and Technology, Glasgow | None M _t | Kirpatrick [15] | 1957 | 152.4 | 101.6 | 63.5 |
| Cornell University, Ithaca | 1, inverse | Broms and Casabrian [7] | 1965 | 254 | 127 | 76.2 |
| Ljubljana University | None M _t | Sulkje and Drnovsek [23] | 1965 | 80 | 64 | 40 |
| University of Cleveland | 1 | Saada and Baah [16] | 1967 | 127; 177 | 71 | 51 |
| GNI, Moscow | 3 | Lomize [5] | 1969 | 180 | 310 | 250 |
| University of Los Angeles | 4 | Lade [17] | 1981 | 100; 400 | 220 | 180 |
| Imperial College, London | 3 | Symes [28] | 1983 | 254 | 254 | 203 |
| Imperial College, London | 3 | Nishimura <i>et al.</i> [43] | 2005 | 195 | 100 | 71 |
| EUDIL, Lille | 2 | Chehade <i>et al.</i> [39] | 1985 | 180 | 180 | 150 |
| ENTPE, Lyon | 2 | Robinet <i>et al.</i> [40] | 1983 | 180 | 180 | 150 |
| ENTPE, Lyon | 2 | Duttine [41] | 1996 | 120 | 200 | 160 |
| University of Tokyo | 3 | Towhata and Ishihara [33,34] | 1985 | 104 | 100 | 60 |
| GDS, U.K. | 4 | GDS | 1994 | | 100 | 60 |
| LCPC, Paris | 1 | Khemissa [38] | 1992 | 150 | 100 | 70 |
| University College of Dublin | 4 | Kelly and Naughton [42] | 2002 | 200 | 100 | 70 |

n Servo-control of tests

The servo-control of the three axes (F , M_t and p_e, p_i) associated with the apparatus makes it possible to impose original loading paths, whether in stresses or strains, in the aim of analyzing the influence of principal axis rotation (see **Fig. 3**). The opportunity to apply an internal pressure different from the external pressure has enabled dissociating the stress rotation angle from the principal stress coefficient b .

n Data acquisition

The axial force F and torque M_t are both measured using a stress gauge sensor, carrying the brand FGP and shaped like a hollow coil (13), placed as shown in [Figure 7](#). The spring balance is positioned inside the cell, just above the specimen, to ensure that friction does not affect the force measurement.

Both the cell pressure p_e and pore pressure u are measured by classical membrane sensors. Axial displacement Δh is measured thanks to an incremental encoder connected to the press motor. An angular position sensor $\Delta\theta$ (18) is placed at the end of the splined shaft. This set-up is referred to as an incremental encoder. The radial strains of the exterior and interior specimen faces ΔR_{ei} and ΔR_{ii} are measured by six LVDT sensors (15) embedded 5 mm deep into the stroke. Two measurement devices, each comprising three sensors positioned at 120 degrees, float between two water levels and track the vertical and radial displacements of the measurement points ([Fig. 9](#)). System floatability is achieved through use of PVC floats, thereby developing the required Archimedes' thrust, in which the sensors are bonded. Return springs then provide for permanent contact of the keys with the specimen surface. The radial displacement measurements of the exterior and interior specimen faces, in addition to the specimen axial strain and rotation of its generatrices, serve to determine average values of the strain tensor components.

For comparative purposes, since the creation of the first modern hollow cylinders during the 1980's, the displacement sensors used can be placed into two categories: contact-free proximity sensors; and electrolytic sensors, such as those employed at Imperial College and University College of Dublin. The first category yields the radial displacement of the specimen, while the second provides vertical and shear displacements.

Calibration proves necessary prior to use of the equipment. Such a step is carried out by placing the configuration in series with a calibration sensor. A calibration bench for torque sensors has been specially developed, and the equipment may also be used for pavement vane testing.

All external sensors are bonded to three cylindrical PVC floats laid out on a ring. Since this arrangement cannot be disassembled, the calibration is performed by means of two alesometers (bore meters) (85-100 and 100-120 mm) adapted to the specimen's external diameter. Periodic verification is performed with either cylindrical spacers or spacers of various diameters (90, 100 and 110 mm).

TESTING PROCEDURES

n Specimen production

Samples are extracted onsite by a sampler 200 mm in diameter and 600 mm high developed at Laval University in Quebec [44]; the core drill is composed of two tubes: an internal tube, whose lower part finishes by a tapered, sharp-edged cutting shoe without any internal offset (constituting the sampling tool); and an external tube, fitted on its lower part with a crown gear that may be attached to the internal tube during lowering of the core drill to the sampling level and when raising the sample towards the surface. Sampling rules are applied so as to obtain Class 1 samples, as per French Standard NF P 94-202. The core drill dimensions respect the rules set forth in this document, devoted to sampling, in particular for: the surface index, internal clearance index, external clearance index, and bevel angle on the cutting shoe.

The samples are then brought to the laboratory in the form of thick soil slabs, from which the specimens will be cut. This cutting step must be performed without modifying the soil water

content, hence in a humid atmosphere (i.e. relative humidity greater than 50%) and at constant temperature. A specimen, 1 to 2 cm longer than the selected height, is trimmed into the sample extracted from its container. The plane cylinder surfaces, at this point, are only approximately parallel.

The advised specimen cutting technique with minimal disturbance, which depends on the definitive geometry, consists of using a vertical shaft grinder (**Figs. 10a** and **10b**). The rough specimen is placed between two rotating and parallel plates. Two eccentric guide rods with respect to the grinder shaft provide support to ensure a regular cut, to be performed by slowly rotating the specimen and removing the shavings that become smaller when nearing the final diameter (the eccentricity of these guide rods is such that the specimen contains an unfinished side and a finished side).

For soft soils, this cutting step is carried out with a tensioned wire, as shown in **Figures 10a** and **10b**. For stiff soils, a large and relatively rigid knife will be used or a motorized vertical lathe along with an adapted tool offering controlled displacements.

For clays containing gravel or hardened concretions, the effort is made to avoid pulling out these elements upon completion of the cutting stage, and the external cylinder surface is accepted with irregularities. Yet, it must also be ensured that these irregularities do not risk damaging the membrane. Should the accidental extraction of an element create a hole, some finer material from the cut shavings would be used to very delicately patch the hole. Once the lateral cut is completed, the average diameter D_e of the specimen is measured (**Fig. 10c**).

The specimen is then placed in a Dural mold, composed of two half-shells, which itself is placed onto a supporting frame (**Figs. 11** and **12**). The interior of each half-shell is lined with aluminum foil in order to avoid bonding. Several successive drilling steps are executed manually using bits with internal diameters sized at 70 mm (**Figs. 12a, b and c**). During this operation, the end plates that serve as drill bit guides are holes with a successive diameter of 20, 40, 60 and 70 mm. Once the cutting step has been completed, the average internal diameter D_i of the specimen is measured (**Fig. 13**).

The specimen then gets placed either into a gauge composed of a thin tube split along a generatrix or in a "V"-shaped cradle whose lower part corresponds to one-third of a circle with a radius equal to that of the specimen. The height of the split tube and the cradle length both equal the theoretical specimen height. The upper and lower surfaces are trimmed by using the gauge for support. The average height H_o of the specimen is also measured.

Ultimately, the specimen produced is a hollow soil cylinder of height $H = 15$ cm, internal diameter $D_i = 7$ cm and external diameter $D_e = 10$ cm. The internal and external diameters are measured along 6 different axes (2 perpendicular axes in each of the 3 horizontal planes lying at 1/4, 1/2 and 3/4 of the specimen height). The specimen height is measured with a caliper along two perpendicular directions. The number of measurements is increased in the event of irregularities. The generatrices must be perpendicular to the plane surfaces, while the specimen diameter must correspond to the diameter of the lower base at ± 0.2 mm. Small local irregularities on the diameter pose no inconvenience.

The specimen is immediately weighed with a scale accurate to within a decigram. At least three specimens are prepared. If the assembly cannot be arranged right away, the specimens are protected by a sheet of aluminum foil (or plastic food wrap) and then placed in an enclosure at 90% humidity.

n Specimen packing

The lower and upper bases accommodate the porous stones plus a set of twelve knives 4 mm high placed radially around the perimeter. The overconsolidated soils, swelling soils and unsaturated soils are all placed on dry porous discs. The normally-consolidated soils are positioned between porous discs saturated in deaerated water, with the drainage circuits remaining saturated. A sheet of filter paper is to be preliminarily inserted between the specimen and porous discs.

In order to facilitate pore pressure homogenization in the specimen during the test, a lateral drain made of filter paper and initially saturated with deaerated water is placed around the specimen (see Fig. 14). To ensure that this drain does not introduce any parasitic forces, it has been created from a strip of the same surface area as the cylinder, with an opening cut out every half-centimeter in the direction of the generatrices.

Specimen assembly then proceeds according to the following procedure (Fig. 15):

1. fastening of the internal membrane to the lower base;
2. installation of the specimen, which remains contained within its Dural mold;
3. filling of the internal membrane at mid-height with silicone oil so as to bring this membrane into contact with the internal surface of the specimen and placing radial displacement sensors;
4. placement of the cap along with the porous stone and knives;
5. fastening of the internal membrane by O-ring;
6. demolding of the specimen and removal of the aluminum foil; and
7. assembly of the external membrane.

Once the cell has closed, a number of operations still need to be carried out before entering the control phase. These operations entail filling the cell by pumping and retracting the jacks that support the set of internal and external radial displacement sensors. In the presence of air bubbles, a bleeding step is also performed. The twelve sensors are all connected to the monitoring console, as illustrated in Figure 6.

The control PC then shifts to the "set-up" screen and the software, developed at LCPC, runs the "swelling measurement" phase.

n Swelling measurement

Specimen assembly proceeds using dry porous discs. By maintaining the drainage circuits dry and open, a cell pressure equal to two-thirds of the effective *in situ* vertical stress σ'_{v_0} is applied, in order to avoid swelling risks during saturation.

Both the top and bottom porous discs are quickly saturated by water circulating within the double drainage circuits, where a preliminary vacuum had been created, for example through use of a water suction pump. These circuits are then connected to one another and hooked up to the system for measuring drained volume; the volume pressure controller developed at the CECP serves to detect and quantify water movements.

If the trend favors water absorption, cell pressure is increased until reaching stabilization; on the other hand, if the trend favors water discharge, pressure is lowered. After stabilization, the soil specimen lies at its initial volume and at the hydrostatic swelling stress u_i . A back pressure then gets applied.

n Application of back pressure

Saturation is achieved by applying a back pressure. This back pressure is gradually raised in increments: 50, 100, 200, 400 and (ultimately) 800 kPa. The transition from one threshold to the next takes place as water absorption speed drops below 0.1 cm³/hr. Cell pressure is adjusted incrementally so as to maintain the same consolidation stress, and the quantities of absorbed or discharged water are recorded. The final pressure is then held until stabilization of the drained volume variations.

n Verification of saturation and measurement of coefficient *B*

Once the drainage has been closed, a cell pressure variation Δp_{cell} of 50 kPa is applied and the pore pressure variation δu measured vs. time. The coefficient $B = \Delta u / \Delta p_{\text{cell}}$ can then be deduced. If the response time required to obtain a stable value exceeds 10 minutes for soft soils and sands and 1 hour for stiff soils, and if the stabilized value reflects a degree of saturation less than $S_r = 0.99$, then the back pressure is increased by increments of 50 kPa until reaching a satisfactory value for coefficient *B*.

n Consolidation

Consolidation consists of applying a constant cell pressure and eventually a given axial load or torque, also applied at a constant value. During this consolidation phase, the back pressure previously defined is kept at the same value. The volume change vs. time relationship is determined using measurements of the water volume discharged from the specimen.

The graph of volume variation during the consolidation phase vs. the square root of time is shown on the screen. The consolidation phase ends once the volume variation drops below the criterion set by the operator or is manifested by a series of points aligned along a slightly-sloped asymptotic direction, which allows the program to deduce the time required to reach the end of consolidation and to calculate the theoretical speed chosen for the test.

"*K*₀" consolidation refers to a specific type of consolidation in which cell pressure is tied to the increase in vertical stress, as a function of cross-section variation, as calculated from information provided by the three internal diameter sensors and the three external diameter sensors. When axial stress reaches the estimated level of *in situ* stress, calculating the ratio of effective horizontal stress to effective vertical stress allows estimating the (thrust) coefficient of earth pressure at rest *K*₀ in the natural soil.

Figure 16 displays the consolidation phase "*K*₀" produced for Guiche clay.

The analysis of *K*₀ ratio variation for all triaxial tests conducted on hollow cylindrical specimens of undisturbed natural soils shows that both the cutting procedure and geometric shape of the specimen tend to override the initial stress state and that this phenomenon remains independent of either the particle dimensions or clay percentage.

n Application of a stress path

Figure 17, extracted from Saada and Townsend [12], depicts the relations between parameters *b* and α , present within the various devices described above. In the case where p_i and p_e are equal, *b* and α are correlated by the simple relation:

$$b = \sin^2 \alpha \quad (3)$$

This relation serves to delimit the zone that may be explored by such devices. The zone can be drawn by the sine curve between the triaxial compression test CT and the triaxial extension test ET (**Fig. 17**).

The improvement in techniques has made it possible to impose increasingly-complex stress paths. The first machines simply introduced a vertical displacement and constant cell pressure. But real stress paths, whether including small cycles or not, could then be applied thanks to a verification performed using information from local displacement measurements.

Figure 18 summarizes the standard paths imposed within the space composed of the Cambridge plane complemented by the stress rotation axis. The first graph corresponds to a path where the deviator is raised, based on an average pressure value by a fixed strain speed. For the initial tests, torsion was applied all the way until the rupture state; it then became possible, prior to reaching torsional rupture, to continue increasing the deviator for a maintained level of torsion.

The studies conducted at Imperial College dealt with paths lying closest to reality, on which the deviator increase is correlated with the rise in average pressure by the coefficient of earth pressure at rest (K_0) [45]. This type of test is intended to approximate the consolidation phenomenon observed *in situ* (**Fig. 18b**).

In the natural world, during slope erosion or an engineering construction project for example, stress rotation occurs simultaneously with deviator increase. For this reason, the third type of path seems all the more justified (**Fig. 18c**). Nonetheless, the lack of *in situ* data on this simultaneity does not enable defining this path type with precision.

The cyclic type paths that seek to simulate earthquakes or wave effects consist of crossing back and forth over this third path.

LCPC has developed a program able to dialogue, via the Ethernet network, with the local servo-control program developed by the CECF (**Fig. 19**); it imposes stress path monitoring by means of calculating path deviation using measurements obtained from the sensors, control states as well as from end-of-stroke states, and then sends the necessary recovery guidelines.

The program designed by CECF contains six modes: home screen, manual mode, specimen placement, consolidation, test, and end-of-test. The LCPC program, on the other hand, is composed of two subsets (**Fig. 20**). The first requires the user to input the geometric parameters, some physical parameters of the soil constituting the specimen, along with the stress path. The second subset comprises the central module and serves to manage the program's major functions. Test phases are organized sequentially and entail measuring: swelling, introduction of back pressure, consolidation and shear.

Figure 21 shows an example of the torsion test on a hollow cylinder of Guiche clay. These figures indicate that the shear phase of the test proceeds satisfactorily (gradual plasticization of soil during deviator increase, **Figs. 21a** and **21b**; plasticization during torsion, **Fig. 21c**). A few torsional torque variations arise however, causing divergence from the actual monitored path (in red), with respect to the imposed path (in green) (**Fig. 22**).

n Test completion

The procedures and observations performed upon test completion are the same for all test types, i.e.:

1. stop the press or loading jacks without introducing any axial unloading;
2. close the drainage circuits in order to limit water absorption during disassembly;
3. empty the cell and quickly withdraw the specimen from the base, then weigh the specimen to the nearest decigram; and

4. record the type of fracture (homogeneous, shear plane, shear plane inclination with respect to the vertical, any other observations) (**Fig. 23**).

SAMPLE RESULTS

A hollow cylinder triaxial test enables obtaining an angle of friction value for all principal stress combinations. For the various types of soils, results are presented in **Figure 24a** for clays and **24b** for sands. The tests were conducted with different loading paths, as detailed in references [7,21,46]. It is nonetheless quite likely that these results depend on test boundary conditions.

Current LCPC equipment makes it possible to study the natural and undisturbed soils of three sites:

- the Pasteur Underpass site in the city of Rouen through sandy clays;
- the experimental Geodelft site, near Almere, in the Netherlands through muddy soil; and
- the experimental LCPC site in Guiche with an organic clay.

These soils have been submitted to an experimental campaign that includes oedometric tests, conventional triaxial tests and tests on hollow cylindrical specimens. The tests conducted on hollow Guiche clay cylinders have, as a priority, served to validate test procedures and control programs; moreover, the equipment capacity has made it possible to monitor the distinct stress paths. Tests were carried out under drained conditions and with equal internal and external specimen pressures, which limits the range of stress paths explored. No definitive conclusions can thus be drawn regarding the effect of stress rotation on the angle of internal friction of Guiche clay.

For the sandy clay in Rouen, the angle of internal friction decreases with stress rotation until reaching a rotation angle of 70 degrees, after which the angle of friction rises slightly. The values obtained do not entirely agree with the curves found in the international body of literature. This difference stems from the fact that the triaxial tests on hollow cylindrical specimens have been performed on soil extracted at a different depth from that considered in triaxial tests.

For the Almere soil, the variation in angle of internal friction vs. stress rotation angle is similar to that observed in the literature for clayey soils. The relation between parameter b and angle of friction however exhibits an opposite shape than that reported in the literature. As a matter of fact, the drained and undrained triaxial tests at LCPC were run at a confinement pressure exceeding the preconsolidation pressure. Specimen strains in the shear phase, which follows the consolidation phase, were probably insufficient to successfully attain the critical state curve. The angles of internal friction could, as a result, be underestimated.

Figure 25 displays the results obtained at LCPC along with a selection of bibliographical resources in terms of angle of friction evolution, as represented here in the form of slope M of the critical state line in the plane (p',q) with respect to principal stresses b [44]. The bibliographical study reveals that the angle of friction value at rupture depends on: the type of apparatus used, specimen shape, test procedure, stress path imposed, and obviously the quality and nature of the soil tested.

The majority of experiments conducted in the past have considered the internal and external pressures to be identical. Results from the thesis work by K. Nasreddine [47], undertaken at LCPC with tests using a constant b value, have highlighted that tests conducted by dissociating b from α would cause earlier specimen ruptures, due to application of an internal

pressure on the hollow cylinder required to maintain b at a value of 0.5. Some authors have already observed this trend [7]. The drop in maximum soil strength with principal stress rotation attests to the influence of this rotation on the stress-strain relation.

An analysis of the initial results obtained by LCPC both in the laboratory and *in situ* has led to proposing a simple theoretical model to account for stress rotation when modeling soil masses interacting with structures [47,51].

CONCLUSION

The benefit of conducting tests on a hollow cylinder of natural soil for the purpose of enhancing knowledge on the mechanical behavior of soils surrounding structures is now fully recognized by the entire soil mechanics community. Yet, only a few laboratories have become equipped with the necessary apparatuses. At present, LCPC possesses a high-performance set-up, which has been validated and well adapted to studying undisturbed natural soils (i.e. the PTCC press). This device, the only one of its kind in France, has already yielded valuable results and moreover served to introduce improvements in the theoretical models inherent in finite element computation packages (like CÉSAR-LCPC). This research is being pursued in multiple directions, in particular in the areas of: small strains and elasticity modulus characterization, influence of anisotropy on plastic flow laws, and cyclic loading effects combined with the creep of clayey soils. Major advances are anticipated for this equipment, in conjunction with accomplishments at LCPC for perfecting *in situ* soil surveying techniques.

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